AN INVENTORY AND ANALYSIS OF CONTROL MEASURES FOR METHANE FOR BRITISH COLUMBIA

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EXECUTIVE SUMMARY

Methane is one of the several greenhouse gases that contribute to global warming. The present day methane concentration within the atmosphere has more than doubled since the pre-industrial levels and is increasing by one percent every year (EPA, 1990).

This study's objective was to prepare an inventory of methane emissions and sources from natural and anthropogenic sources in B.C. for the years 1990 and 2005. Methane reduction opportunities as well as control measures associated with the most suitable options for the major anthropogenic sources of methane emitters in B.C. were also studied and discussed.

The inventory was organized into nine anthropogenic and four natural methane source categories. These categories are:

Anthropogenic

- Landfills
- Manure
- Natural Gas Industry
- Domestic Animals
- Prescribed Fires
- Oil Industry
- Mobile Combustion Sources
- Incineration
- Stationary Combustion Sources

Natural

- Wetlands
- Wildfires
- Wildlife
- Lakes and Rivers

The majority of the information used to complete the methane emissions inventory were obtained from discussion with the industry and the government representatives. The Energy, Mines and Petroleum Resources (EMPR), provided most of the energy consumption estimates used for the Mobile and Stationary combustion sources. The cooperation received from the industry and government agencies were invaluable in making this inventory as complete and accurate as possible.

Latest emission factors were obtained from a number of sources. For instance, Adhoc Committee, Environment Canada's National Methane Inventory (Jaques, 1991), and numerous similar studies done by U.S. EPA and Levelton Associates were used.

Methane uptake by the atmosphere and aerobic soils were estimated for B.C. information from literature provided the bans for estimating the magnitude of these services.

Annual methane emissions in B.C. for 1990 and 2005 by major source sectors are shown in Figure S-1. Emissions form natural sources are also shown in Figure S-1.

The top four anthropogenic methane emitters account for about 87% of the total anthropogenic sources for 1990 and 2005. Landfills being the largest in the anthropogenic category and wetlands for the natural sources.

A number of technical control measures were selected for implementation in the short- and long-terms. Attention was given to the control measure that were thought to have acceptable economic and social impacts. The measures selected are best considered an illustrative of the levels of control possible.

The short-term and long-term reduction in methane emissions achieved by the selected control measures is depicted by Figure S-2. A 13% reduction relative to 1990 could be achieved in the short-term. The reduction achieved increases to 27% relative to emissions in 2005, in the long-term. The long-term control measures yield a net emission of 412 kg, 23% lower than the 533 kt emitted in 1990. The net emission in 2005 after control are 11% lower than the net emissions after short-term control.

The study yielded a number of recommendations which, if implemented, would improve the inventory of methane emissions and promote the implementation of emission control measures. These may be summarized briefly as follows:

- review the economic barriers of landfill gas recovery systems;
- verify and develop a computer model for analysis of emissions from landfills;
- review landfilling regulations;
- develop alternatives to reduce landfilling of woodwastes;
- develop a code of practice for the natural gas production industry;
- conduct a detailed study to quantify fugitive emissions from the natural gas production industry;
- conduct a detailed study of economic incentives for methane emissions control measures;
- manure treatment systems on dairy farms should be encouraged;
- conduct a detailed analysis to determine methane emissions from landfilling of woodwastes and pulpmill wastes due to the uncertainty in the preliminary estimates made in this study.

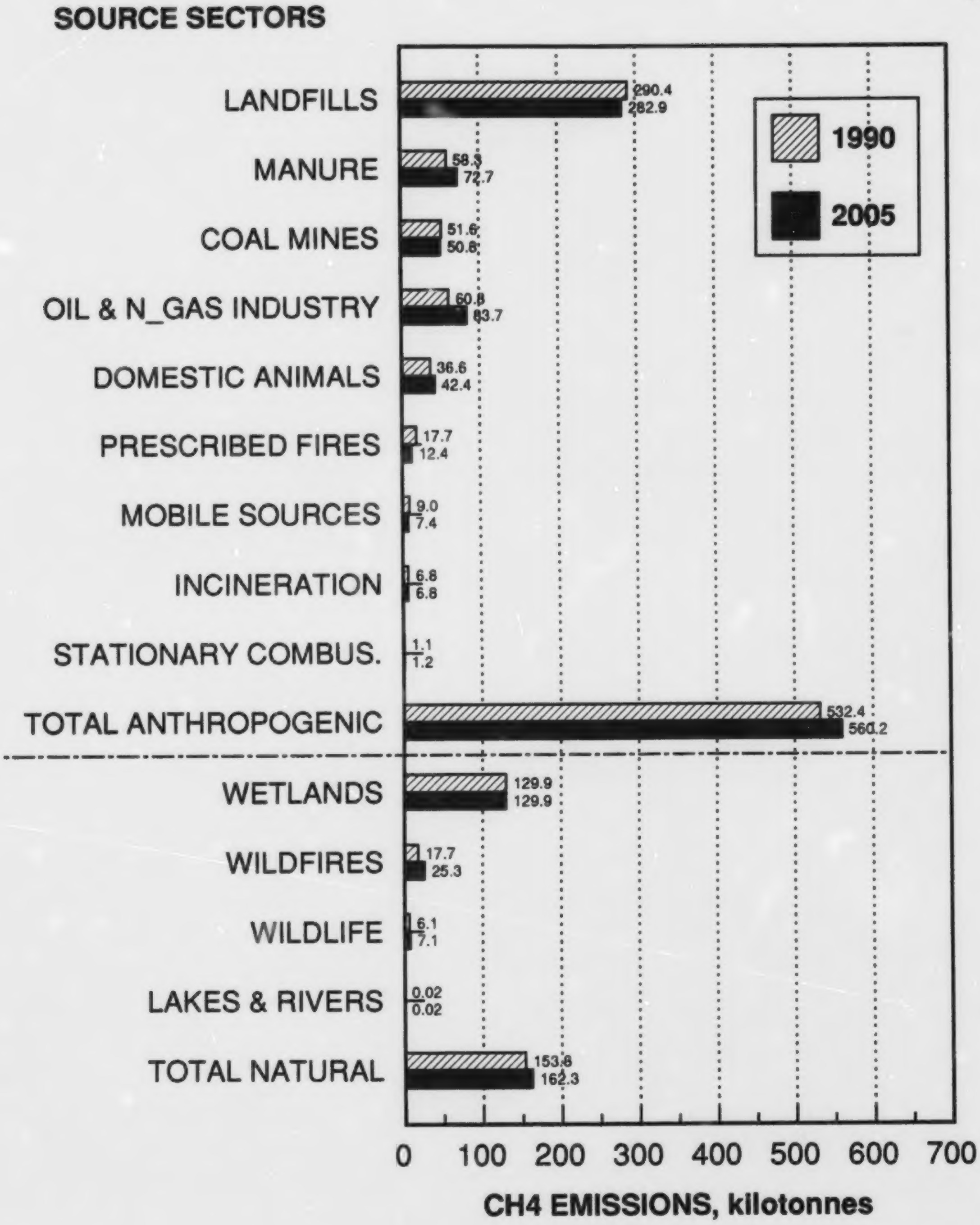


FIGURE S-1 CH4 EMISSIONS BY MAJOR SOURCE SECTORS IN BC

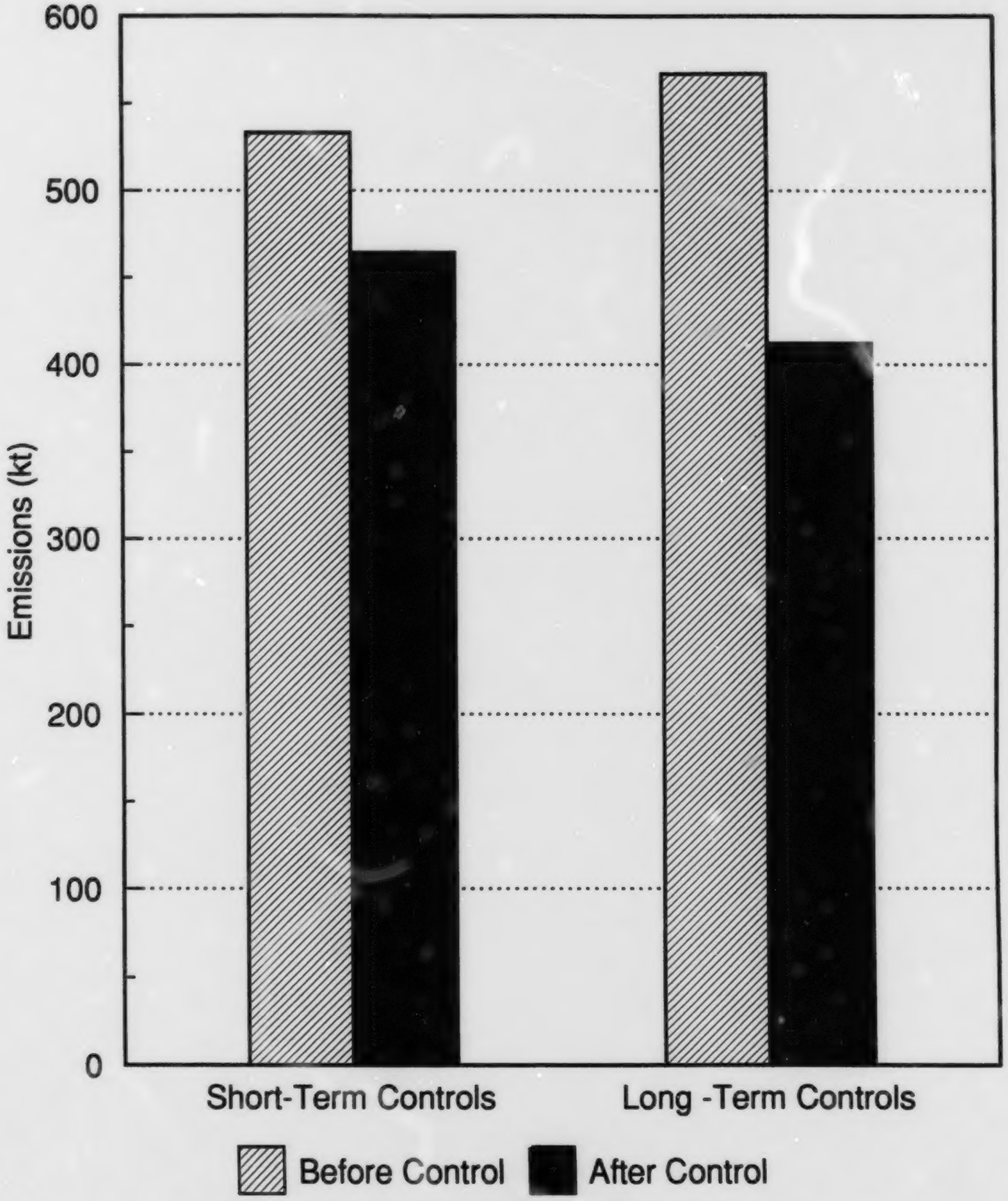


FIGURE S-2 METHANE EMISSION REDUCTION POTENTIAL IN BC

I. INTRODUCTION

A. BACKGROUND

Methane gas is one of the several greenhouse gases that contribute to global warming. At present, the average methane global concentration is increasing by one percent every year (IPCC, 1990). The present day atmospheric concentration of CH_4 is more than double the pre-industrial value (IPCC, 1990).

Releases of methane to the atmosphere occur from natural as well as from human activities. Major natural sources of methane are wetlands, wild animals and wild fires. Major global anthropogenic (man-made) sources of CH_4 are landfills, manure piles, domestic animals, natural gas systems, coal mining, rice production and fuel combustion. Of the seven major anthropogenic sources, all but rice production applies to British Columbia.

An inventory of methane emissions from anthropogenic and natural sources in Canada has been prepared by Environment Canada (Jacques, 1991). However, an inventory of methane emissions in British Columbia has not previously been prepared. One of the objectives of this study was to prepare an inventory of CH_4 emissions and sinks from both natural and anthropogenic sources in British Columbia for 1990 and 2005. Another objective was to discuss available CH_4 reduction opportunities as well as technologies and impacts associated with the most suitable options for the top emission sources in B.C.

B. SCOPE OF WORK

The main project objectives were as follows:

1. Prepare an inventory of methane in B.C. for both anthropogenic and natural sources for 1990. Contributions from individual source sectors were to be determined using accepted methodologies and best available statistics.

2. Prepare an inventory of methane sinks in the province for 1990.

3. Project a methane inventory for the year 2005, assuming no new policies or regulations are implemented to reduce methane emissions.

4. Develop a list of control measures and technologies that can reduce methane emissions in both the short and long term.

5. Estimate the technical potential of each measure for reducing methane emissions in the short and the long terms.

6. Discuss the technologies and impacts of CH_4 reduction opportunities for major sources of methane emissions as well as cost-effectiveness and economic viability of these measures/technologies.

II. METHODOLOGY USED FOR THE METHANE INVENTORY

A. ANTHROPOGENIC SOURCES

1. Landfills

(a) Municipal Solid Waste

Landfill gas is generated from anaerobic decomposition of refuse in municipal solid waste (MSW) landfills. Typical products of decomposition of waste are methane, carbon dioxide, and non-methane organic compounds, the principal constituents being methane and carbon dioxide.

Methane emissions from landfills were estimated using the Scholl Canyon computer model developed by the U.S. EPA. The model requires certain landfill characteristics to be entered in order to calculate methane emissions. The data required for calculation are chemical composition of MSW, methane generation rate constant (k), methane generation potential (L_o), MSW disposal history and efficiency of the gas collection system.

For MSW, default values of 50% methane, 50% carbon dioxide and 8000 ppm non-methane organic compounds were used. The methane rate constant (k) is a function of moisture content, temperature, pH and nutrients. Values of k were estimated based on mean daily temperature and annual precipitation for the specific geographic location of the landfill. The k values used in the model are shown in Table II-1 for each region. The methane potential constant (L_o) is dependant on the type of refuse placed in the landfill. If the cellulose content of the refuse is high, then a higher value of L_o should be used. For MSW landfills, a L_o value of 230 m^3 CH_4/Mg of refuse was used in the model (Kuo, 1990).

TABLE II-1 TEMPERATURE, PRECIPITATION AND k VALUES USED FOR THE INVENTORY CALCULATIONS

Region	Kinetic Rate Constant, k yr^{-1}
British Columbia	
Campbell River	0.028
Chilliwack	0.028
Courtenay	0.028
Kamloops	0.01
Matsqui	0.028
Port Alberni	0.028
Prince Rupert	0.028
Lower Fraser Valley	0.028
Burnaby	
Coquitlam	
Delta	
Maple Ridge	
North Vancouver	
Richmond	
Surrey	
Vancouver	
Vernon	0.01
Victoria	0.028
Other	0.025

Source: El Rayes and Edwards, (1991)

The total annual amount of MSW disposed of in B.C. was calculated as the product of the population and the annual rate of MSW disposed of per capita. Table II-2 shows the per capita disposal factors used in this study. Major landfill operators were contacted to obtain detailed information about the type and the amount of waste deposited in the landfill since its inception and whether a landfill gas collection system was in operation. The difference between the total amount of waste disposed of, minus the amount disposed off in major landfills, minus the amount incinerated, was considered to be disposed of in many smaller landfills in the region. For calculation purposes, the amount disposed of in these many smaller landfills was assumed to be deposited in a single collective landfill. The quantities of solid waste disposal in B.C. are shown in Table II-3 for the period from 1941 to 2005.

The historical data for each landfill, appropriate k and L_o values, and the gas collection efficiency were entered into the computer model to estimate methane emissions from each landfill for the base year 1990 and the forecast year 2005. MSW disposal per capita was assumed to decrease from 1.75 kg/day/capita in 1990 to 0.88 kg/day/capita in 2000 according to the Ministry of Environment's goal to reduce MSW to 50% by the year 2000 through reduction, reuse and recycling efforts. The same reduction factor was applied for the year 2005 (see Table II-2).

(b) Wood Waste

In order to adapt the Scholl Canyon computer model for estimating methane emissions from landfilled wood waste, values for L_o, k, and the historical data for wood waste disposal are needed. As a first approximation, L_o and k values were estimated based on the carbon content of wood relative to MSW. Using a typical carbon content for wood of 52% (BHLA, 1983) the L_o value was estimated to be 413 m^3 CH_4/Mg of wood waste. Similarly, the k value was estimated to be 0.01 1/yr. Wood waste disposal data is available for 1978 (Appleby, 1978) and 1989 (McWilliams, 1990). These were related to lumber production for their respective years, i.e. ratio of dry

TABLE II-2 PER CAPITA MSW DISPOSAL FACTORS USED IN THIS STUDY

Year	Per Capita Disposal[a] kg/day
1940	0.88
1945	0.88
1950	0.88
1955	0.88
1960	0.88
1965	0.97
1970	1.07
1975	1.37
1980	1.75
1985	1.75
1990	1.75
1995	1.32
2000	0.88[b]
2005	0.88

[a] Interpolate linearly between years stated for those not shown

TABLE II-3 MSW INCINERATED AND LANDFILLED IN BRITISH COLUMBIA

Year	Disposed of (tonnes)	Incinerated (tonnes)	Landfilled	
			(tonnes)	(%)
1941	263,097	0	263,097	100
1942	274,271	0	274,271	100
1943	285,445	0	285,445	100
1944	296,618	0	296,618	100
1945	307,792	0	307,792	100
1946	318,966	0	318,966	100
1947	330,140	0	330,140	100
1948	341,314	0	341,314	100
1949	352,488	0	352,488	100
1950	363,661	0	363,661	100
1951	374,835	0	374,835	100
1952	389,842	0	389,842	100
1953	404,849	0	404,849	100
1954	419,856	0	419,856	100
1955	434,863	0	434,863	100
1956	449,870	0	449,870	100
1957	464,708	0	464,708	100
1958	479,545	0	479,545	100
1959	494,383	0	494,383	100
1960	509,220	0	509,220	100
1961	534,539	0	534,539	100
1962	561,602	0	561,602	100
1963	589,534	0	589,534	100
1964	618,358	0	618,358	100
1965	648,100	0	648,100	100
1966	678,783	0	678,783	100
1967	715,339	0	715,339	100
1968	753,086	0	753,086	100
1969	792,056	0	792,056	100
1970	832,284	0	832,284	100
1971	899,504	14,600	884,904	98
1972	968,862	14,600	954,262	98
1973	1,042,907	14,600	1,028,307	99
1974	1,121,933	14,600	1,107,333	99
1975	1,206,256	14,600	1,191,656	99
1976	1,296,205	14,600	1,281,605	99
1977	1,391,679	14,600	1,377,079	99
1978	1,493,459	14,600	1,478,859	99
1979	1,601,938	14,600	1,587,338	99

TABLE II-3 MSW INCINERATED AND LANDFILLED IN BRITISH COLUMBIA (continued)

Year	Disposed of (tonnes)	Incinerated (tonnes)	Landfilled	
			(tonnes)	(%)
1980	1,717,532	14,600	1,702,932	99
1981	1,753,028	14,600	1,738,428	99
1982	1,771,519	14,600	1,756,919	99
1983	1,790,009	14,600	1,775,409	99
1984	1,808,500	14,600	1,793,900	99
1985	1,826,990	16,352	1,810,638	99
1986	1,845,481	16,352	1,829,129	99
1987	1,884,204	16,352	1,867,852	99
1988	1,922,927	211,752	1,711,175	89
1989	1,961,650	239,752	1,721,898	88
1990	2,000,373	239,752	1,760,621	88
1991	1,921,188	239,752	1,681,436	88
1992	1,848,970	239,752	1,609,218	87
1993	1,773,629	239,752	1,533,877	86
1994	1,695,164	239,752	1,455,412	86
1995	1,613,576	239,752	1,373,824	85
1996	1,528,865	239,752	1,289,113	84
1997	1,441,030	239,752	1,201,278	83
1998	1,350,072	239,752	1,110,320	82
1999	1,255,991	239,752	1,016,239	81
2000	1,158,787	239,752	919,035	79
2001	1,174,583	239,752	934,831	80
2002	1,190,378	239,752	950,626	80
2003	1,206,174	239,752	966,422	80
2004	1,221,970	239,752	982,218	80
2005	1,237,766	239,752	998,014	81
2006	1,253,562	239,752	1,013,810	81

tonnes landfilled and lumber production in millions of board feet (MMfbm), then this ratio was used to extrapolate over the last 30 years using available lumber production statistics. Statistics of lumber production were obtained from Statistics Canada and Council of Forest Industries (COFI). These values are tabulated in Table II-4.

Historical landfill data and L_o and k values were entered into the model to obtain a crude estimate of methane emissions from wood waste landfills. For calculation purposes, it was assumed that wood waste was deposited in one large collective landfill.

(c) Pulping Waste

Primary clarifier sludge and some sludge from secondary wastewater treatment from pulp and paper mills are landfilled in British Columbia at many mills. For this pulping waste, 3% of pulp production was used as an estimate of the waste being landfilled. Pulp production statistics for the past 30 years were obtained from COFI statistical tables and are tabulated in Table II-5. L_o was taken to be the same as that for MSW, since the carbon composition is approximately 25% in pulp sludge (Edwards & Quan, 1991). The rate constant (k) was taken to 0.025 1/yr because of the high moisture content of the waste. These parameters were entered into the computer model to obtain a crude estimate of methane emissions from pulping waste landfills. For calculation purposes, it was assumed that the pulping waste was deposited in one large collective landfill.

2. Manure

Methane can be produced from manure by the action of bacteria when under anaerobic conditions and in a wet and warm environment. The environment necessary for the production of methane from manure is only encountered when the manure is stored in wet lagoons or deep pits. In British Columbia manure from animals and poultry other then dairy cattle, feedlot

TABLE II-4 ESTIMATE OF WOODWASTE LANDFILLED IN BRITISH COLUMBIA

YEAR	TOTAL LUMBER PRODUCTION MMFBM	INDUS. WASTE LANDFILLED Dry tonnes	CUMULATIVE LANDFILLED Dry tonnes
1960	5,505	527,049	527,049
1961	5,379	505,680	1,032,729
1962	6,265	578,134	1,610,863
1963	6,391	578,705	2,189,568
1964	6,702	595,272	2,784,840
1965	6,936	604,056	3,388,896
1966	7,440	635,078	4,023,974
1967	7,148	597,787	4,621,762
1968	7,841	642,178	5,263,939
1969	7,715	618,512	5,882,451
1970	7,764	609,008	6,491,459
1971	9,005	690,774	7,182,233
1972	9,523	714,035	7,896,267
1973	10,441	764,803	8,661,071
1974	8,783	628,160	9,289,231
1975	7,469	521,262	9,810,492
1976	10,745	731,305	10,541,797
1977	12,038	798,481	11,340,277
1978	12,545	810,407	12,150,684
1979	12,518	787,007	12,937,691
1980	11,980	732,457	13,670,148
1981	10,424	619,290	14,289,438
1982	10,109	583,087	14,872,525
1983	13,043	729,756	15,602,281
1984	13,078	709,089	16,311,370
1985	14,003	735,017	17,046,388
1986	13,335	676,885	17,723,272
1987	15,888	778,989	18,502,261
1988	15,574	736,650	19,238,911
1989	15,236	694,305	19,933,216
1990	14,203	622,660	20,555,875

TABLE II-5 ESTIMATED PULP WASTE LANDFILLED IN BRITISH COLUMBIA

YEAR	TOTAL PULP PRODUCTION kilotonnes	PULP WASTE LANDFILLED tonnes	CUMULATIVE LANDFILLED tonnes
1960	1,927	57,810	57,810
1961	2,047	61,410	119,220
1962	2,187	65,610	184,830
1963	2,269	68,070	252,900
1964	2,565	76,950	329,850
1965	2,971	89,130	418,980
1966	3,328	99,840	518,820
1967	3,509	105,270	624,090
1968	3,972	119,160	743,250
1969	4,426	132,780	876,030
1970	4,100	123,000	999,030
1971	4,409	132,270	1,131,300
1972	4,453	133,590	1,264,890
1973	5,166	154,980	1,419,870
1974	5,272	158,160	1,578,030
1975	3,951	118,530	1,696,560
1976	5,347	160,410	1,856,970
1977	4,877	146,310	2,003,280
1978	5,382	161,460	2,164,740
1979	5,324	159,720	2,324,460
1980	5,717	171,510	2,495,970
1981	4,813	144,390	2,640,360
1982	4,759	142,770	2,783,130
1983	5,752	172,560	2,955,690
1984	5,371	161,130	3,116,820
1985	6,029	180,870	3,297,690
1986	6,354	190,620	3,488,310
1987	7,060	211,800	3,700,110
1988	7,170	215,100	3,915,210
1989	6,990	209,700	4,124,910
1990	6,604	198,120	4,323,030

cattle, hogs and lay hens and pullets is either normally too dry or dropped in a pasture or range where it dries naturally under aerobic conditions. For this reason, only manure that may be handled and stored anaerobically was considered to produce methane.

Methane is produced from the "volatile solids" or organic matter in the manure. The amount of volatile solids produced by the various classes of livestock and poultry was calculated from their populations and factors for volatile solids production published by The Society for Engineering in Food and Agriculture, American Society of Agricultural Engineers (1989). The amount of methane produced from the volatile solids was calculated on the basis of 186.16 gm of methane/kg of volatile solids produced from cattle and hogs and 200.48 gm of methane/kg of volatile solids produced from poultry (Safley and Westerman, 1988). The results of these calculations are presented in Table II-6 for the base year, 1990. The estimated methane production from manure in the year 2005 is given in Table II-7.

3. Coal Mines

Methane is generated as a by-product while coal is being formed. It then exists in pores and fractures in the coal, as well as being absorbed on the coal itself. The absorbtion capacity of coal depends on its rank, moisture content and the amount of mineral matter present. Absorbtion increases with pressure and rank, while the presence of water and mineral matter reduce the absorbtion capacity (Hollingshead, 1990).

In B.C. there are eight active coal mines of which seven are large mines. Two are in the Northeast region and five are in the Southeast region of British Columbia. These mines are shallow and the coal is expected to be friable and, hence, disposed to releasing the methane content quickly (Hollingshead, 1990).

Methane emissions from coal mines in British Columbia were estimated based on methane content of the coals and the quantities of raw coal production for 1990. The Ministry of Energy, Mines and Petroleum Resources

TABLE II-6 METHANE PRODUCTION FROM DOMESTIC LIVESTOCK AND POULTRY MANURE FOR 1990

Animal Class	Animal Numbers	Volatile Solids Production kg/day	Volatile Solids Production tonnes/year	Methane Production tonnes/year
Dairy Cattle				
Lactating	65600	6.000	143600	26730
Dry	12800	6.000	28080	5230
Replacements	28000	4.500	45990	8560
Calves	28000	2.000	20440	3810
Beef Cattle				
Brood Cows	228000	3.960	329550	Aerobic
Bulls	11000	5.760	23130	Aerobic
Replacements	420000	2.880	44150	Aerobic
Feedlot	33400	2.880	11530	2150
Calves	228000	1.800	149806	Aerobic
Sheep				
Ewes and Rams	25400	0.460	4260	Aerobic
Replacements	5000	0.276	503	Aerobic
Market Lambs	45000	0.276	200	Aerobic
Goats				
Milking	10000	0.460	1680	Aerobic
Meat	10000	0.276	1010	Aerobic
Hobby	10000	0.460	1680	Aerobic
Hogs				
Sows	22700	1.403	11620	2160
Boars	1500	1.700	930	170
Market	340200	0.425	25300	4710
Poultry				
Lay Hens	2408000	0.024	21090	4230
Lay Pullets	2408000	0.008	2830	570
Market Broilers	46558000	0.017	36410	Aerobic
Market Roasters	2245000	0.031	4850	Aerobic
Broiler Breeders	451000	0.039	6470	Aerobic
Breeder Replacements	451000	0.013	920	Aerobic
Turkeys				
Light	819000	0.041	3080	Aerobic
Heavy	1131000	0.091	12970	Aerobic
Horses	75000	5.000	136880	Aerobic
			1068930	58310

TABLE II-7 PROJECTED METHANE PRODUCTION FROM DOMESTIC LIVESTOCK AND POULTRY MANURE FOR 2005

Animal Class	Animal Numbers	Volatile Solids Production kg/day	Volatile Solids Production tonnes/year	Potential Methane Production tonnes/year
Dairy Cattle				
Lactating	856700	6.000	187660	34930
Dry	16800	6.000	36700	6830
Replacements	36600	4.500	60100	11190
Calves	36600	2.000	26710	4980
Beef Cattle				
Brood Cows	250800	3.960	443530	Aerobic
Bulls	12100	5.760	31120	Aerobic
Replacements	46200	2.880	59420	Aerobic
Feedlot	36700	2.880	15510	2890
Calves	220000	1.800	201610	Aerobic
Sheep				
Ewes and Rams	25400	0.460	4270	Aerobic
Replacements	5000	0.276	500	Aerobic
Market Lambs	4500	0.276	200	Aerobic
Goats				
Milking	10000	0.460	1680	Aerobic
Meat	10000	0.276	1010	Aerobic
Hobby	10000	0.460	1680	Aerobic
Hogs				
Sows	22700	1.403	11620	2180
Boars	1500	1.700	930	170
Market	340200	0.425	25300	4710
Poultry				
Lay Hens	2408000	0.024	21100	4230
Lay Pullets	2408000	0.008	2830	570
Market Broilers	95554000	0.017	74720	Aerobic
Market Roasters	4392000	0.031	9490	Aerobic
Broiler Breeders	926000	0.039	13280	Aerobic
Breeder Replacements	926000	0.013	1890	Aerobic
Turkeys				
Light	1400000	0.041	5260	Aerobic
Heavy	1934000	0.091	22170	Aerobic
Horses	750000	5.000	136880	Aerobic
			1397140	72660

(MEMPR) provided the raw coal production figures for the base year and the coal production forecast for the year 2005. The minimum estimated emissions from B.C. mines is 31.6 x 10^6 m^3/yr, while the maximum of 174 x 10^6 m^3/yr is based on the "in-place" methane content of coals (Hollingshead, 1990). Due to the fact that Western Canadian mines are shallow and the residual gas does not desorb readily; it was assumed that only 54% of the total residual gas desorbs. (Jaques, 1991). Methane will be released not only from the coal being mined but also from the exposed faces of the mine during the mining process. This emission was assumed to be approximately three times that of the mined coal release which is the same methodology as used by Environment Canada to estimate surface mine emissions for the national inventory (Jaques, 1991).

Applying the above assumptions, 12.3 kt methane is released from the coal being mined and 36.9 kt methane from exposed surfaces. Therefore the total annual methane emission is 49.2 kt. In 1990, 25.8 million tonnes of coal was mined in B.C. (MEMPR). Hence, an average emission rate of 2 kg CH_4 per tonne of coal mined was used.

4. Oil and Gas Industry

Methane emissions from oil and gas operations are estimated as a percentage of the total oil or gas production or throughput for each of the following sectors: production; processing; transmission or transport; and distribution. Emissions from facilities in Canada, the USA, Japan and Western Europe are less than the overall 2 - 4% leakage commonly assumed in global studies (IPCC, 1990); which assumes all "unaccounted for" gas listed in operational records is emitted to the atmosphere rather than simply being the result of metering error or accounting differences.

Emission sources for the oil and gas industry typically include fugitive losses (leaks) from valves, fittings etc; process venting from wells (casing gas, well tests, etc.), gas-operated devices (controllers, chemical pumps, etc.) and combustion emissions such as from flaring or engines. Data on the number, size, type, age, operating characteristics and condition of equipment in use by industry are required in order to assemble an inventory.

Of the emission factors available in the literature those developed in the past year (Picard & Koon, 1990) for the Canadian Petroleum Association (CPA) for a preliminary inventory of VOC and CH_4 emissions from the upstream oil and gas industry in Alberta were assumed for this study (see Table II-8). No study of comparable detail was available for the industry in B.C., and at least one company in B.C. (Petro-Canada, 1991) is using the CPA results for its internal greenhouse gas inventory. Esso Resources Canada Limited is conducting their own study (ESSO, 1991). The use of emission factors developed for Alberta means some implicit assumptions regarding equipment and operating practices are carried into this inventory.

The CPA inventory comprises Phase I of a three phase study being conducted. Phase II currently underway is an evaluation and verification of the data and assumptions used in the Phase I inventory, and is being based on monitoring data collected for this purpose. Phase III will provide an analysis of cost-effective measures to control CH_4 and VOC emissions.

For the CPA inventory, data on facilities in place in Alberta were provided by the Alberta Energy Resources Conservation Board (ERCB) for the number of wells and major facilities such as batteries and processing plants (Picard & Koon, 1990). The number of minor facilities such as line heaters and dehydrators was estimated based on assumed typical design practices, while equipment schedules developed from equipment control lists and process and mechanical drawings for some selected facilities were used to approximate the amount of equipment at those facilities across the Province. Estimates of emissions of (total) hydrocarbons (THCs) from these facilities were obtained by a variety of techniques, including the use of average emission factors, empirical correlations, simulations, fuel consumption and production statistics, and some emission data available. Methane and VOC emissions were estimated using the THC speciation profiles for each emission source category.

TABLE II-8 SUMMARY OF TOTAL HYDROCARBON (THC) EMISSION FACTORS FOR THE OIL AND GAS INDUSTRY

Source	Reference	THC Emission Factor (Mass %)	Industry & Literature Range
GAS INDUSTRY:			
Gas Production	CPA, 1990	.39	.20 - .39
Gas Processing	CPA, 1990	.11	.037 - .11
Gas Transmission	CPA, 1990	.03	.018 - .61
Gas Distribution	Can.Gas Assoc. 1990	0.03*	.03 - .3
OIL INDUSTRY:			
Oil Production	CPA, 1990	1.43	1.35 - 1.43
Oil Transportation	CPA, 1990	0.05	
LVP Transmission	CPA, 1990	0.07	
HVP Transmission	CPA, 1990	0.04	

* Methane Emission Factor

Note: LVP and HVP refer to low vapour pressure (natural gas liquid or NGL) and high vapour pressure (liquefied petroleum gas or LPG) products, respectively.

The methane emission factor for gas distribution was taken as that recommended by the Canadian Gas Association (CGA) based on monitoring data (CGA & ONGA, 1990). This sector was not reviewed in the CPA report.

Emissions were not tabulated here for categories for which preliminary calculations indicated losses to be quite low (LNG production; well servicing and testing; drilling) relative to the major categories, and for accidental releases, which were believed low (6.8% of total in the CPA study) and would vary unpredictably with each year.

Base quantity data for British Columbia are shown in Table II-9. Volumes estimated for oil and gas production, gas distribution, and oil, HVP and LVP transport were made for purposes of this inventory only. It was assumed that future gas production from fields within B.C. would meet the predicted domestic demand, so imports of gas would not comprise a significant portion of the supply in 2005 and production related methane emissions were assigned for the total gas demand. Production volumes were used as the base quantity in gas processing as that was implicit in the emission factor presented in Volume I of the Picard & Koon (1990) report. No allowance was made for the production emissions associated with oil that was imported to the Province (i.e. emissions from oil production in Alberta were not included in this inventory even though oil was destined for B.C.)

Gas transmission and distribution volumes were based on data for Westcoast Energy Inc., as other approximations were lower. The other estimates were provided by the MEMPR for transmission, and by B.C. Gas and Pacific Northern Gas for distribution.

Density and composition data vary with producing field and amount of processing. For gas production and processing, the values shown in Table II-9 were based on inlet conditions at Westcoast Energy Inc.'s MacMahon gas plant, which serves several gas fields. Since Westcoast processes and transmits most of the gas in the Province, these values were assumed representative for the industry. Data from B.C. Gas likewise were used for the transmission and distribution subsectors.

Table II-9: Base Quantity Data for the Oil and Gas Methane Emission Inventory for British Columbia

Sector	Volume (Gm3) 1990	Volume (Gm3) 2005	Gas Properties: Density (kg/m3)	Gas Properties: CH4 Content Mole%	Gas Properties: CH4 Content Mass%	Comments
Gas						
Production, Processing	13.8	24.3	0.81	86	71.5	1990 volume approx. by MEMPR (P.Comm., 1991) 2005 volume prorated from sec. demand in MEMPR (1990) forecast, assuming potential reserves will meet this demand. Density & Composition for Westcoast McMahon Inlet Processing volumes set equal to production (required for the processing emission factor).
Transmission	11.36	20	0.81	95.5	91.1	1990 vol. (401 billion ft3) from Westcoast annual report; higher than MEMPR approx. (P.Comm.'91). 2005 volume prorated from 1990 market gas fraction of raw gas, as (11.36/13.8)*24.3 Gm3. Density & Composition BC Gas typical specs
Distribution	6.485	11.42	0.694	95.5	91.1	1990 vol. (229 billion ft3)=Westcoast domestic pipeline; 12% higher than total of BC Gas and PNG. 2005 volume prorated from 1990 domestic distribution and market gas fraction, as (229/401)*(11.36/13.8)*24.3 Gm3. Density & Composition BC Gas typical specs
Oil	(m3)		Liquid	Associated Gas CH4 Content		
Production	1.96E+06	7.91E+05	850	86	71.5	1990 & 2005 volumes approx. by MEMPR (P.Comm., 1991) Oil density as per CPA report for Alberta (Picard & Koon, 1990) Gas composition as per Westcoast McMahon Inlet
Transport Crude Oil	6.57E+06	1.13E+07	850	10*	5	Includes production within B.C. and imports/exports. 1990 & 2005 oil production volumes approx. by MEMPR (P.Comm., 1991); 1990 import by Trans Mountain Pipe Line totalled 4.61 X 10^6 m3, while the forecast of 10.54 x 10^6 m3 for 2005 was est. from primary req'ts in MEMPR (1990) Oil density & gas composition from Picard & Koon (1990) report for Alberta
HVP	7.00E+05	1.23E+06	500	10*	5	1990 volume approx. by MEMPR (P.Comm., 1991) 2005 volume prorated from 1990 HVP and raw gas production and 2005 raw gas forecast. HVP density & gas composition from Picard & Koon (1990) report for Alberta
LVP	3.00E+05	5.27E+05	700	10*	5	1990 volume approx. by MEMPR (P.Comm., 1991) 2005 volume prorated from 1990 HVP and raw gas production and 2005 raw gas forecast. LVP density & gas composition from Picard & Koon (1990) report for Alberta

* 10 mole % specified in CPA report (Picard & Koon, 1990) converts to 3.6% by mass. It is conservatively estimated here as 5% by mass.

N.B.: (1) Gas composition (mol%):

(a) Production and Processing - 85.97% C1, 5.62% C2, 2.27% C3, 1.08% C4, 0.37% C5, 0.22% C6+, 0.31% N2, 2.11% CO2 and 2.05% H2S
(b) Transmission and Distribution - 95.5% C1, 3.0% C2, 0.5% C3, 0.2% C4+, 0.6% N2 and 0.2% CO2

(2) Emission calculated as: Throughput (Mass) * Emission Factor (Mass %) * Methane Content of Gas (Mass %), where Throughput = Volume * Density

e.g. Methane emissions from gas production in 1990: 13.8 Gm3 * 0.81 Kg/m3 * 0.39% * 71.5% * 10E-6 kt/kg = 31.2 Kilotonnes CH4 Emission

Estimates of density and gas composition for oil, HVP and LVP production and transport were taken from the CPA study for Alberta, with the only exception being the associated gas composition for oil which was taken as the Westcoast McMahon inlet value.

No estimate of error was given in either the CPA report (Picard & Koon, 1990) or the CGA statement (CGA & ONGA, 1990).

5. Domestic Animals

The total annual production of methane from livestock and poultry was calculated as the product of the population of the various classes or production groups of these animals and an appropriate annual methane generation factor. The annual generation factor for methane from animals was determined from their digestible energy (DE) intake and the proportion of that energy lost as methane. The annual methane generation from poultry was calculated from their metabolizable energy (ME) intake and the proportion of that energy lost as methane. In all cases, energy intake was assumed to equal requirements.

Methane is produced in the intestine of animals by anaerobic microbial fermentation of ingested feedstuffs. The methane gas produced is lost to the animal through eructation, respiration and flatulation and represents an energy loss to the animal that does not show up in the faeces. Digestible energy (DE) is the gross energy intake minus that not recovered in the faeces. Thus, the energy lost as methane represents a portion of digestible energy DE. In poultry, faeces and urine are excreted together and as a consequence the normal unit of energy requirement in poultry is metabolizable energy (ME). In the case of poultry, methane loss represents a portion of ME. Measurement of this loss requires expensive respiration calorimetry apparatus. For this reason, efforts have been made to derive prediction equations that express methane in terms of the caloric value of methane lost as a percentage of energy intake of the total ration (Blaxter and Clapperton, 1965).

The methane production by the individual was calculated as a percent of their digestible energy (DE) intake in the case of mammals or their metabolisable energy (ME) intake in the case of poultry. The percentage factors used where either taken directly from the published literature or where calculated from published calorimetric data. A summarization of these data and the associated references is presented in Appendix I. In consideration of these data, it was apparent that feeding corn base rations to ruminants yielded methane levels that were approximately 2 percentage units of DE less than barley-grass-alfalfa based rations. Since ruminant livestock production in British Columbia is based predominantly on barley-grass-alfalfa rations the energy equivalent (kcal) of methane produced was taken as 9% of the DE intake of cattle, sheep and goats. The amount of methane produced in grams was then calculated by dividing the methane energy produced by 13.23 kcal/gCH$_4$. (Report of Sub-Committee on Constants and Factors, European Association For Animal Production, 1965).

For example:

Cow consuming 20000 kcal DE/day
20000 * .09 = 1800 kcal methane/day
1800 * 4 * 187 kJ/kcal = 7537 kJ methane/day
1800 /13.23 = 136 gm methane/day

The percent of DE lost as methane was taken as 0.75% for hogs (NRC, 1988) and 3% for horses (Crutzen, Aselmann & Seiler, 1986; Blaxter & Czerkawski, 1966). The percent of ME lost as methane for poultry was taken as 0.2% for poultry (Gaseway, 1976).

The annual individual production of methane was calculated as the individuals daily production of methane times the normal life span of that animal during the year. Thus feedlot cattle produce 185.7 gm methane/day for 120 days (Table II-10) which equals 22.28 kg methane per animal per year and growing hogs 4.83 gm/day for 172 days etc. This approach rendered the methane production data compatible with the population statistics which originated primarily from marketing records.

The data on the daily and annual production of methane by the various productive groups of livestock and poultry are presented in Appendix I.

TABLE II-10 CRITERIA USED IN THE ESTIMATION OF DIGESTIBLE ENERGY (DE) INTAKE OF LIVESTOCK AND POULTRY

Animal Class	Animal Weight kg.	Criteria Used
Dairy Cattle		
Lactating	600	Producing 20 kg of 3.5% milk/day
Dry	600	30 days before calving
Replacements	450	Yearling Heifers gaining 0.7 kg/day
Calves	200	9 month of age gaining 0.7 kg/day
Beef Cattle		
Brood Cows	550	Dry pregnant having nursed 4 months of year
Bulls	800	Maintenance
Replacements	400	Gaining 0.6 kg/day
Feedlot	400	Gaining 1.2 kg/day for 120 days
Calves	250	Gaining .75 kg/day
Sheep		
Ewes and Rams	50	Maintenance with ewes lactating 3 months/year
Replacements	30	Gaining .150 kg/day
Market Lambs	30	Gaining .300 kg/day for 160 days
Goats		
Milking	50	Medium activity producing 2 kg 4% milk/day
Meat	30	Medium activity at .150 kg/day
Hobby	50	Medium activity
Hogs		
Sows	165	Producing 16 pigs/year
Boars	200	Maintenance
Market	50	Gaining .760 kg/day for 175 days
Poultry		
Lay Hens	2	Consuming .113 kg feed/day containing 2700 kcal ME/kg
Lay Pullets	0.7	Consuming 6.8 kg total feed containing 2860 kcal ME/kg in 140 days
Market Broilers	2	Consuming 3.8 kg total feed containing 3410 kcal ME/kg in 46 days
Market Roasters	3.63	Consuming 8.7 kg total feed containing 3190 kcal ME/kg in 70 days
Broiler Breeders	3.3	Hens consuming .16 kg feed/day containing 2662 kcal ME/kg
Breeder Replacements	1.1	Consuming 11.8 kg total feed containing 2750 kcal ME/kg in 154 days
Turkeys		
Light	4.54	Consuming 11.35 kg total feed containing 3190 kcal ME/kg in 91 days
Heavy	10	Consuming 27.5 kg total feed containing 3080 kcal ME/kg in 126 day
Horses	500	Doing light work

The domestic population for the various classes of livestock in British Columbia for the base year of 1990 was taken from the following sources. Where data was not given for the year of 1990, livestock numbers for 1990 were projected from population trends for previous years.

B.C. Broiler Hatching Egg Sector Profile; December, 1990
B.C. Chicken Sector Profile; February, 1991
B.C. Turkey Sector Profile; November, 1990
B.C. Ministry of Agriculture and Fisheries, B.C. Horse Industry Highlight, 1990
Into the Nineties; Sectoral Profile, Beef Industry of B.C.; October, 1990

Livestock and poultry populations for the year 2005 where projected from the average annual percentage change in their populations for the period of 1980 to 1990. The resulting factor was then applied to the 1990 population with annual compounding to the year 2005. The beef cattle population has increased by 2% per year over the last ten years. However, it was felt that this growth was not sustainable and in fact, growth in this industry would only be 10% to the year 2005.

In the case of sheep, goats and horses, the population statistics where too uncertain to render a judgement for the future and consequently their 2005 population was taken as the same as 1990. The hog population of British Columbia over the last ten years has shown large gyrations with no definite trend. There also seems to be some uncertainty about its future direction. Consequently, no change was projected in its population to the year 2005.

The resulting annual population percentage change factors used to project populations in the year 2005 are as follows:

Dairy Cattle	1.8%	Lay Hens	0.0%
Beef Cattle	0.6%	Broilers	4.9%
Sheep	0.0%	Roasters	4.9%
Goats	0.0%	Broiler Breeders	4.9%
Hogs	0.0%	Turkeys	3.6%
Horses	0.0%		

The DE requirements for the various types of livestock and their production groups were taken from the National Research Council, Nutrient Requirements of: Dairy, 1989; Beef, 1984; Sheep, 1985; Goats, 1985; Swine, 1988; and Horses, 1989.

The ME requirements for poultry were calculated from current industry standards of production. For example lay hens consume 0.113 kg/day containing 2700 kcal ME/kg which equals 305 kcal ME per day.

The productive criteria used in the calculation the respective DE and ME intake of livestock and poultry are presented in Table II-10.

6. Prescribed Fires

Trace quantities of methane are emitted when biomass fuels are burned. The amount of methane released varies by fuel type and combustion environment. In British Columbia, prescribed burns are used to control fire hazards, improvement of wildlife habitat and rangeland, and for silviculture purposes. Prescribed fires were broken down into three categories: forest management, range & wildlife improvements and wild fires. Wild fires are not considered an anthropogenic source and, therefore are reported under natural sources. Methane emissions from these sources were calculated using data from the B.C. Forest Service (Chabot, 1991) and the Cloud Aerosol Research Group (Radke et al., 1989).

Burning for forest management is the largest source of methane in this category while wildlife and range improvement releases are quite low. The number of hectares burnt due to forest management within the province in 1990 was 50,022 hectares and 45,289 hectares for range/wildlife improvements. An average full consumption of 80 tonnes/ha was used for forest management and 20 tonnes/ha for range/wildlife improvement. Average emission factor of 3.5 grams methane per kilogram was assumed for both categories (Chabot, 1991). A 30% reduction in prescribed burning was projected for CH_4 by the year 2005 (BHLA, 1990).

7. Mobile Combustion Sources

(a) Road

The road sector was divided into two fuel types, gasoline and diesel. The gasoline category was further subdivided into five vehicle classes and the diesel category was subdivided into three vehicle classes. The eight vehicle categories are defined in Appendix II-A according to US EPA definition. Subsectors for gasoline are:

- light duty gasoline vehicles (LDGV);
- light duty gasoline trucks 1 (LDGT1);
- light duty gasoline trucks 2 (LDGT2);
- heavy duty gasoline vehicles (HDGV);
- motorcycles (MC).

Subsectors for diesel are:

- light duty diesel vehicles (LDDV);
- light duty diesel trucks (LDDT);
- heavy duty diesel vehicles (HDDV).

Active vehicle population data for 1990 were obtained from the Insurance Corporation of B.C. (ICBC) and distributed accordingly to the above vehicle classes. The average fleet fuel efficiencies for each vehicle class were taken from the Lower Mainland Emission Survey for Mobile Sources (EAG, 1988). These fuel efficiencies are for the 1985 vehicle fleet, however, they were used for the 1990 estimate since no other similar data was available. This yields a conservative estimate, since fuel efficiencies will have slightly improved since 1985.

The average vehicle-kilometres travelled for each vehicle type were obtained from the Canadian version of the Mobile 4 Program (Mobile 4C). Using these, the total fuel consumption for each vehicle class was calculated. Fuel consumption totals of both gasoline and diesel were compared to EMPR 1990 values and were within 10% to 15%. Adhoc Committee emission factors were used to obtain methane emissions for 1990. The forecast for 2005 was developed using a growth factor calculated as the ratio of fuel use in 2005 to that in 1990 from EMPR data. This factor was multiplied by the actual 1990 fuel consumption to obtain 2005 fuel usage for each fuel category. Appropriate Adhoc Committee emission factors, which account for fuel efficiencies, were applied to get 2005 methane emissions forecast. Detailed calculations are in Appendix II-B.

(b) Aircraft, Marine and Rail

Methane emissions for 1990 and 2005 were calculated using EMPR fuel consumption data and appropriate Adhoc Committee emission factors. The emission factors used are shown in Table II-11.

(c) Off-Road Vehicles

Off-road vehicles include those used for logging, mining, farm use and recreational purposes for which road use tax does not apply. Statistics Canada publication 53-218 (1989) provides data on net fuel sales (with road use tax) and gross fuel sales (with and without tax) hence, the difference was taken as fuel used for off-road vehicles. Since 1990 values are not available, 1989 data were used. The fuel used for off-road vehicles was assumed to be the same as in 1990, based on the small decrease in consumption (4%) observed from the statistics for the 1985-1989 period. These assumptions will not significantly impact the CH_4 estimate since this source is so small.

TABLE II-11 METHANE, EMISSION FACTORS FOR TRANSPORTATION SECTOR

	Methane Emission Factor (t/PJ)	
	1990	2005
Gasoline	47.7	30
Aviation Gasoline	11.7	11.7
Aviation Turbo	11.5	11.5
Diesel Auto	4.36	4.63
Rail	7.8	7.8
Marine	45	45
Heavy Fuel Oil		
Marine	40	40

8. Incineration

Methane emissions arise from incineration of woodwaste and MSW as well as Fraser River debris that is burned twice a year. Woodwaste disposal statistics were obtained from a survey done by McWilliams (1990), which provided data on disposition of hog fuel in B.C. The quantity of Fraser River debris burnt every year was obtained from Council of Forest Industries (COFI) through personal communication with Doug Cooper. Data on MSW incinerated was taken from a report done by Levelton Associates for Environment Canada (El Rayes and Edwards, 1991). The annual amount of MSW incinerated up to the year 2005 is given in Table II-3. At present, all incinerators are operating at full capacity in B.C. and, since there are no future plans of another incinerator being built at present, it was projected that the same amount of MSW incinerated will remain constant to 2005. Woodwaste incineration was assumed to remain constant to 2005 (Holm, 1991). Fraser River debris is projected to drop by 15-20% by the year 2005 due to increased utilization of debris (Cooper, 1991), so a 17% reduction was used as a reasonable estimate for this inventory.

The emission factors for woodwaste incineration was estimated at 77 tonnes CH_4 per peta Joule (see Appendix II-C for calculation). 3.5 grams CH_4 per kilogram waste was used for Fraser River debris since it is similar to emissions from prescribed burning. For MSW incinerators an emission factor of 0.23 grams of CH_4 per kilogram of waste was used (CEC, 1990).

9. Stationary Combustion Sources

Small amounts of methane are emitted during combustion of fossil fuels due to incomplete combustion. This category includes all stationary combustion sources i.e. industrial, commercial and residential sectors. These were broken down by fuel types and appropriate emission factors were applied to calculate annual methane emissions. EMPR fuel requirements data for 1990 and 2005 and Adhoc Committee (1990) emission factors were used. However, for utility power, B.C. Hydro provided a value for fuel burned for the year 1990 and boiler emission factors from the California methane inventory was were used (CEC, 1990). The emission factors used are shown in Table II-12.

B. NATURAL SOURCES

1. Wetlands

Information about the wetland areas in B.C. and the methane emission characteristics of wetlands was collected from a variety of sources including published books, government reports and scientific journals. In addition, contact was made with persons likely to be carrying out relevant research or possessing unpublished information. A list of the persons contacted are listed at the end of Appendix III. In addition to valuable opinions and suggestions, the personal contacts also yielded a number of valuable unpublished sources of information.

B.C. was subdivided into ten physiographic regions and areal extent of the total CH_4 -emitting wetlands were estimated. Table II-13 lists the various physiographic regions of B.C. and the corresponding area of methane emitting

TABLE II-12 METHANE EMISSION FACTORS FOR COMBUSTION SOURCES

Fuel	Methane Emission Factor (t/PJ)		
	Residential	Commercial	Industrial
Renewables (excluding wood)	-	-	-
Natural Gas	1.15	1.15	1.3
Non Energy	-	-	0.65
Propane - Transportation	1.1	1.1	1.1
LPG	1.1	1.1	1.1
Gasoline	70	-	-
Kerosene	5.7	0.7	0.16
Aviation Gasoline	-	11.7	-
Aviation Turbo	-	11.5	-
Light Fuel Oil	5.5	0.67	0.16
Diesel	8.3	12.5	12.5
Rail			
Marine			
Heavy Fuel Oil	1.37	1.37	0.82
Marine			
Petroleum Coke	-	-	0.38
Non-Energy RPPs	-	-	0
Industry Own Use RPPs	-	-	1.1
Wood	12	-	4.7
Spent Pulping Liquor	-	-	-
Coals	-	-	0.54
Coke & Coke Oven Gas	-	-	0.51

Adapted from:

Adhoc Committee on Emission factors Energy Mines and Resources, December, 1990.

TABLE II-13 THE AREA OF WETLANDS IN DIFFERENT PHYSIOGRAPHIC REGIONS OF B.C.

Physiographic Region [*a]	Wetland Region [*b]	Total Area (km^2) [*a]	Total Wetland (km^2)	Where Surveyed		Total CH$_4$ - Emitting Wetland (km^2)
				% Organic	% Gleysol	
Hecate Depression	Pacific Oceanic	31,278	1,912	70[*c]	30[*c]	1,395
Georgia Depression	Temperate Pacific	12,095	721	30	70	267
Southern Plateau	Intermountain Prairie	51,329	972	39	61	438
Chilcotin/Caribou Plateau	Intermountain Prairie/Mid Boreal	63,877	2,589	71	29	1,913
Central Plateau	Mid Boreal	87,839	3,486	64	36	2,356
Northwestern Plateau	Mid/High Boreal	68,725	841	65[*c]	35[*c]	576
Liard Plain	High Boreal	15,712	762	65[*c]	35[*c]	522
Alberta Plateau: Fort Nelson Lowland	High Boreal/Low Subarctic	50,290	23,852	89	11	21,491
Peace River Lowland	Mid-Boreal	52,450	9,582	43	57	4,666
Mountain	Mountain	513,410	4,127	8	92	710
						32,334

[*a] The physiographic subdivision is shown in Figure 1 in Appendix III, adapted from Van Ryswyk et al. (unpublished)

[*b] According to National Wetlands Working Group, 1988

[*c] Estimated

wetlands. The ten physiographic regions were further subdivided into five wetland classes according to the Canadian Classification System: Bogs, Ponds, Marshes, Fens and Swamps. Table II-14 shows the breakdown of each physiographic region into the five wetland classes and the annual methane emissions from each class.

A detailed description of the methodology and emission factors used for the inventory are included in Appendix III.

2. Wildfires

Methane releases from wildfires were calculated using data obtained from the B.C. Ministry of Forests (Chabot, 1991). The number of hectares burnt by wildfires within the province in 1990 was 75,365 hectares. An average fuel consumption of 67 tonnes per hectare and an average emission factor of 3.5 grams methane per kilogram were assumed (Chabot, 1991). Using these values, 17,700 tonnes of CH_4 was emitted in 1990.

It is not possible to reliably forecast for wildfires in the year 2005. An average of the previous ten years was used as a reasonable estimate of the area burnt by wildfires in 2005. Statistics for the ten year average were obtained from Ministry of Forests (Chabot, 1991) and amounted to be 108,000 hectares burnt by forest fires per year. The ten-year average for the area burnt by forest fires is higher than experienced in 1990, which is considered a low year for wildfires. Based on the ten year average, CH_4 emissions in 2005 would be 25,326 tonnes.

3. Wildlife

Methane emissions from wildlife were only for ruminants, because ruminants are the major animal producer of methane and population statistics and information on methane production for other wildlife species are lacking. Population statistics for the various classes of wildlife in British Columbia were supplied by the Fish and Wildlife Branch of the Ministry of Environment, Victoria, B.C. The Fish and Wildlife Branch of the Ministry of

TABLE II-14 ANNUAL METHANE EMISSION FROM WETLANDS IN B.C.

Physiographic Region	All CH_4 - EMITTING WETLANDS					ANNUAL CH_4 WETLAND EMISSIONS				
	Beaver Ponds	Marshes	Fens & Swamps	Bogs	Total	Beaver Ponds @ 15	Marshes @ 20	Fens & Swamps @ 5	Bogs @ 0.5	Total
	%	%	%	%	km^2	tonnes/yr using above emission rates in g/m^2yr				
Hecate Depression	2	2	10	86	1,395	419	558	698	600	2,274
Georgia Depression	2	2	40	56	267	80	107	534	75	796
Southern Plateau	4	76	20	-	438	263	6,658	438	-	7,358
Chilcotin-Caribou	4	56	40	-	1,913	1,148	21,426	3,826	-	26,399
Central Plateau	4	20	66	10	2,356	1,414	9,424	7,775	118	18,730
Northwestern Plateau	4	5	56	35	576	346	576	1,613	101	2,635
Liard Plain	4	2	54	40	522	313	209	1,409	104	2,036
Fort Nelson Lowland	2	2	30	64	21,491	6,447	8,596	32,237	6,877	54,157
Peace River Lowland	2	2	34	60	4,666	1,400	1,866	7,932	1,400	12,598
Mountains	2	10	31	55	710	213	1,420	1,100	195	2,929
TOTALS					34,334	12,042	50,840	57,562	9,470	129,913

Environment are projecting that through their habitat enhancement programmes wildlife numbers will increase by 10 to 20 per cent in the next 15 years. On the basis of this information wildlife numbers were projected to have increased by 15 percent by 2005.

Dietary energy requirements are not as well defined for wildlife species as they are with domestic animals. However, it has long been established that the basal metabolism of mammals may be expressed by the equation:

$$\text{basal metabolism} = 70\ W^{0.75}\ \text{kcal/d}$$
$$\text{where } W = \text{body weight (kg)}$$

Wildlife were considered to exist at a maintenance level and the above equation was increased by 20% to account for activity. Thus, the digestible energy (DE) intake of wildlife is:

$$DE = 84\ W^{0.75}\ \text{kcal/d}$$

For lack of better data, the methane production of wildlife ruminants were taken as the same percent of digestible energy intake as that of domestic ruminants (9%). Calculations of the annual methane production per animal based on the DE intake of wildlife are presented in Appendix I.

The average and range of methane emissions from the various types of wildlife in 1990 are presented in Table II-15.

The estimated annual methane production from wildlife in the year 2005 is presented in Table II-16.

4. Lakes and Rivers

Methane production occurs in the anaerobic sediments of freshwater lakes and rivers where organic matter is being decomposed. Production rates are determined primarily by organic matter availability and by temperature (Kelly and Chynoweth, 1981). Methane loss to the atmosphere occurs from

TABLE II-15 AVERAGE AND RANGE OF ANNUAL METHANE EMISSIONS FROM WILDLIFE RUMINANTS FOR 1990

Animal Class	Animal Numbers	Annual Methane Production KJ/Animal	Total Methane Production Tonnes/Year	Range % DE Intake As Methane	Low Methane Production Tonnes/Year	High Methane Production Tonnes/Year
Moose	175,000	17	3,017	7 - 14	2,246	4,793
Elk	40,000	14	556	7 - 14	414	883
Caribou	14,000	9	131	7 - 14	98	209
Sheep						
Thinhorn	12,000	5	61	7 - 14	45	96
Bighorn	7,700	7	55	7 - 14	41	87
Mountain Goat	56,000	6	341	7 - 14	254	542
Deer						
Black-tailed	35,000	5	1,767	7 - 14	1,315	2,807
White-tailed	48,000	5	242	7 - 14	180	385
TOTAL			6,169		4,593	9,802

TABLE II-16 PROJECTED METHANE PRODUCTION FROM WILDLIFE IN THE YEAR 2005

Animal Class	Animal Numbers	Annual Methane Production KJ/Year/Animal	Total Methane Production Tonnes/Year
Moose	201,250	17	3,469
Elk	46,000	14	639
Caribou	16,100	9	151
Sheep			
Thinhorn	13,800	5	70
Bighorn	8,855	7	63
Mountain Goat	64,400	6	392
Deer			
Black-tailed	402,500	5	2,032
White-tailed	55,200	5	279
TOTAL			7,094

emitted bubbles, from diffusion through the porous stems of aquatic plants (Dacey and Klug, 1979), or through limited surface exchange when lakes turnover, primarily in the fall (Rudd and Taylor, 1980). Most of the research to date has focused on the role of methanogenesis and methane oxidation in carbon cycling (Rudd and Hamilton, 1978; Kelly and Chynoweth, 1981; Lilley et al., 1988). The only published measurements of annual methane emission from northern lakes found by the current study were the data from beaver ponds (Ford and Naiman, 1987; Naiman et al., 1991; Vitt et al., 1990)

Consequently, the study estimates of freshwater methane emission are based on yet unpublished results from studies of shallow lakes in the Hudson Bay Lowland and deeper oligotrophic lakes in the Experimental Lakes area near Kenora (Dr. John Rudd, personal communication). According to Dr. Rudd, emission from shallow lakes averages 200 to 300 mg m^{-2} d^{-1} (15 to 45 g m^{-2} yr^{-1}). Methane emission to the atmosphere is 2 to 4 orders of magnitude lower from the deeper lakes. Even in the eutrophic deep lakes that turnover, Dr. Rudd stated that little methane escapes from the hyperlimnion (<1 g m^{-2} yr^{-1}).

Boyd (1983), quoting Farley (1979), stated that the area of freshwater lakes in B.C. is 2 x 10^6 ha. The B.C. Environment and Land Use Secretariat (1976) reports that the area of freshwater surfaces in B.C. total 2.3 x 10^6 ha. Assuming that 25% of this surface is on shallow lakes emitting 30 g m^{-2} yr^{-1}, the methane emission from this source is 1.7 x 10^4 kg yr^{-1}. Given the lack of information on methane emission and areas for the different lake types, the error associated with this estimate is high, probably in excess of 200%. The emission estimate should be modified as future data becomes available.

III. METHANE EMISSIONS INVENTORY

A. TOTAL ANTHROPOGENIC AND NATURAL SOURCES

1. Annual CH_4 Emissions by Source Sector

Landfills are the largest anthropogenic source of CH_4 emissions in B.C., followed by manure and coal mines as the second and third largest sources, respectively. Values of both anthropogenic and natural sources are reported in Table III-1 and Figure III-1 for the base year (1990) as well as for the year 2005. The total anthropogenic methane emissions in B.C. were estimated at 532,371 tonnes for 1990 and 550,946 tonnes for the year 2005. The total anthropogenic sources for 1990 are listed in Table III-3 and illustrated by Figure III-2. Similarly, Table III-4 and Figure III-3 show methane emissions from anthropogenic sources for the year 2005.

Natural source emissions of methane are 153,750 tonnes for 1990 and 162,325 tonnes for 2005. The increase is primarily due to wild fires and wildlife. The area burnt by wild fires in 1990 is lower than the average over the past ten years.

CH_4 emissions from landfills, coal mines, prescribed fires and mobile sources will decline by the year 2005, while all other anthropogenic sources will increase (Figure III-1).

The total anthropogenic methane emissions for Canada were estimated to be 3.8 million tonnes for 1987 (Jaques, 1991). Based on this value, anthropogenic emissions in B.C. are about 14% of the national total. Methane emissions for B.C. and Canada are tabulated in Table III-2 by major source sectors.

TABLE III-1 ANTHROPOGENIC AND NATURAL METHANE EMISSIONS FOR 1990 AND 2005

ANTHROPOGENIC SOURCES	CH_4 EMISSIONS (tonnes)	
	1990	2005
Landfills	290,405	282,891
Manure	58,315	72,657
Coal Mines	51,600	50,800
Oil & Natural Gas Industry	60,843	83,657
Domestic Animals	36,618	42,427
Prescribed Fires	17,736	12,415
Mobile Combustion Sources	8,991	7,392
Incineration	6,795	6,788
Stationary Combustion	1,068	1,179
Total Anthropogenic	532,371	560,206
NATURAL SOURCES		
Wetlands	129,913	129,913
Wild Fires	17,673	25,326
Wildlife	6,147	7,069
Lakes & Rivers	17	17
Total Natural Sources	153,750	162,325
Total from all Sources	686,121	713,271

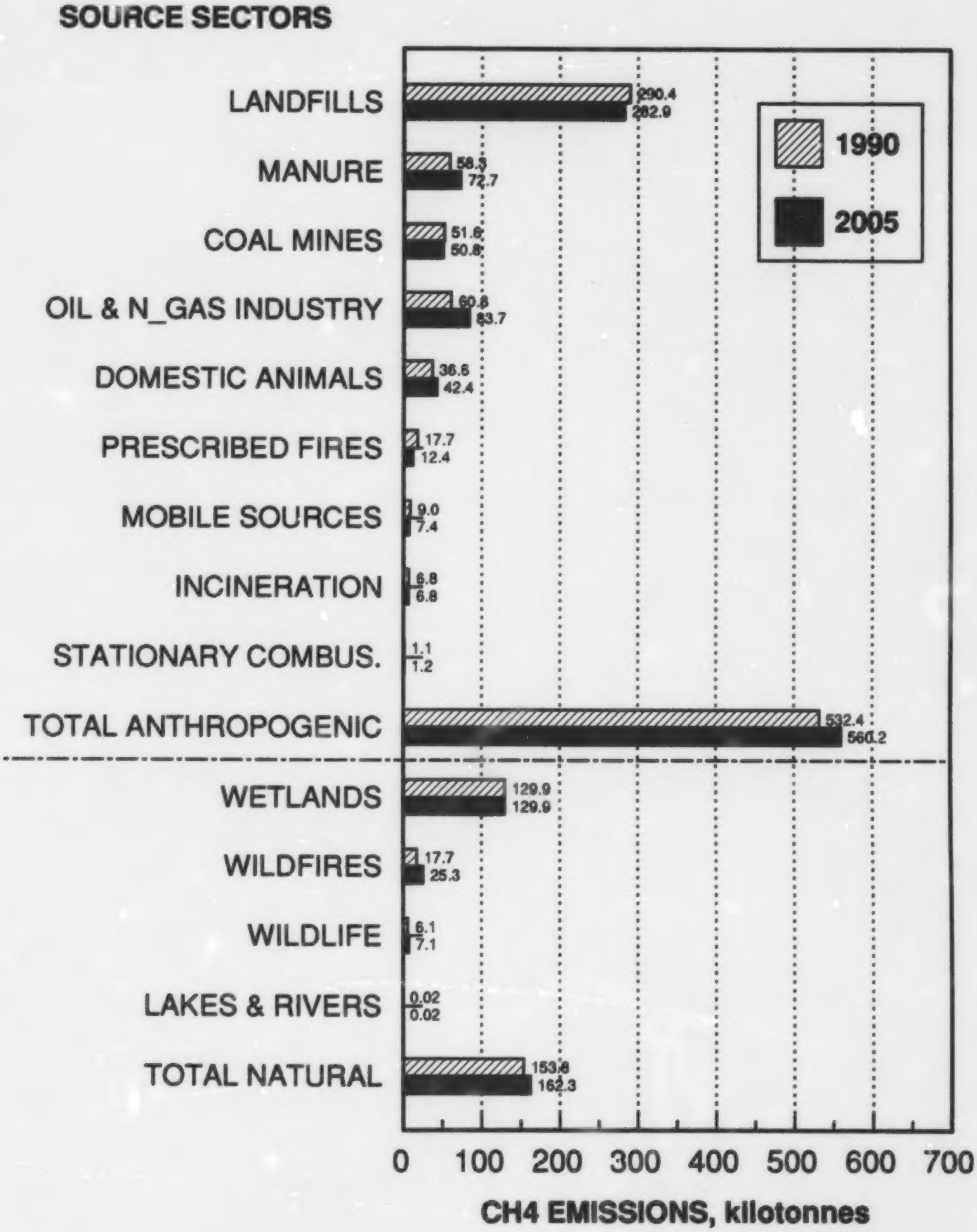


FIGURE III-1 CH4 EMISSIONS BY MAJOR SOURCE SECTORS IN BC

TABLE III-2 CH_4 EMISSIONS FOR MAJOR SOURCE SECTORS IN B.C. AND CANADA

ANTHROPOGENIC SOURCES	CH_4 EMISSIONS (kilotonnes/year)		% B.C.
	B.C. (1990)	CANADA (1987)	
Landfills	290.4	1850[a]	15.7
Manure	58.3	330	17.7
Coal Mines	51.6	140	36.9
Oil & Natural Gas Industry	60.8	270	22.5
Domestic Animals	36.6	900	4.1
Prescribed Fires	17.7	80	22.1
Mobile Combustion Sources	9.0	-	-
Incineration	6.8	-	-
Stationary Combustion	1.1	230	0.5
Total Anthropogenic	532.3	3800	14.0
NATURAL SOURCES			
Wetlands	130	24,000	0.5
Wild Fires	17.7	980	1.8
Wildlife	6.1	150	4.1
Lakes & Rivers	-	-	
Total Natural Sources	153.8	25,130	0.6
Total from all Sources	686.1	28,930	2.4

[a] Municipal waste landfills only. El Rayes and Edwards (1991) has determined methane emissions from MSW landfills for 1990 to be 1,406 kt.

TABLE III-3 ANTHROPOGENIC EMISSION SOURCES IN BC (1990)

	tonnes CH4 (1990)
LANDFILLS	290,405
STATIONARY COMBUS.	1,068
MANURE	58,315
INCINERATION	6,795
COAL MINES	51,600
MOBILE SOURCES	8,991
N_GAS LEAKS	43,555
OIL LEAKS	17,288
PRESCRIBED FIRES	17,736
DOMESTIC ANIMALS	36,618
TOTAL	532,371

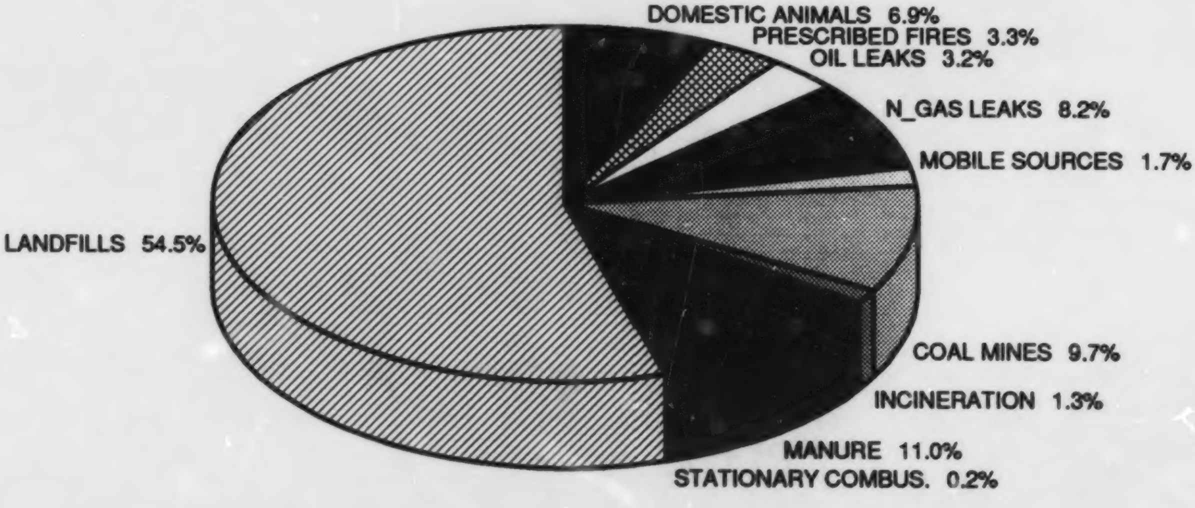


FIGURE III-2 ANTHROPOGENIC EMISSION SOURCES IN BC (1990)

TABLE III-4 ANTHROPOGENIC EMISSION SOURCES IN BC (2005)

	tonnes CH4 (2005)
LANDFILLS	282,891
STATIONARY COMBUS.	1,179
MANURE	72,657
INCINERATION	6,788
COAL MINES	50,800
MOBILE SOURCES	7,392
N_GAS LEAKS	76,537
OIL LEAKS	7,120
PRESCRIBED FIRES	12,415
DOMESTIC ANIMALS	42,427
TOTAL	560,206

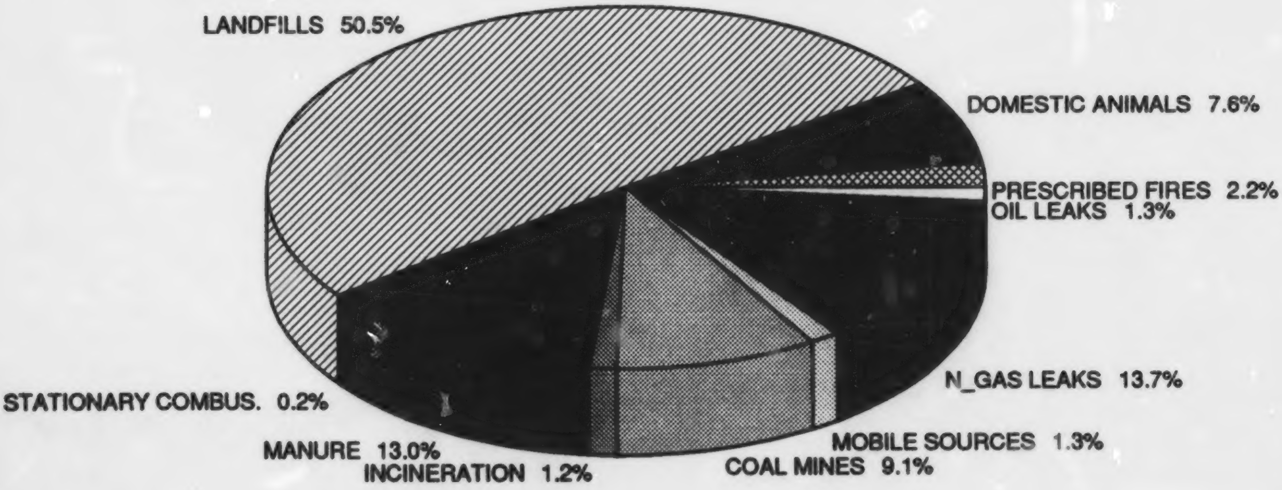


FIGURE III-3 ANTHROPOGENIC EMISSION SOURCES IN BC (2005)

(a) Landfills

Landfills account for 54.5% of the total anthropogenic methane emissions, or 290,405 tonnes CH_4 for 1990. Emissions from municipal solid waste (MSW), woodwaste, and pulp waste for 1990 and 2005 are listed in Table III-5 and shown in Figure III-4. The MSW subsector is the major emitter of CH_4 from landfills. In 1990, 79% of the total landfill emissions were from MSW, 17% from woodwaste and 4% from pulp waste. Methane emissions from MSW landfills will be reduced by 15% by the year 2005 due to reduced waste disposal and installation of methane recovery systems at some additional major landfills. Estimates of CH_4 emissions from woodwaste and pulp waste are very approximate because of the lack of historical landfill disposal data and should be modified as future data become available.

(b) Manure

Manure sources of CH_4 emissions in B.C. are tabulated in Table III-6 for 1990 and 2005. Manure sources contributed 58,315 tonnes of CH_4, or 11% of the total anthropogenic methane emissions in B.C. for 1990, making it the second largest source in B.C. Dairy cattle are the largest emitter in this sector, amounting to 76% of the total. The next largest source of CH_4 in this category is manure from hogs and poultry (other subsector), accounting for 20%.

In the year 2005, emissions from dairy cattle manure will contribute to 80% of the total, or 57,926 tonnes of CH_4. Emissions from beef cattle manure will remain the same as in 1990, where as emissions from hog and poultry manure will shrink to 16%. Figure III-5 illustrates the percent CH_4 emissions of various subsectors for the years 1990 and 2005.

(c) Natural Gas Industry

Methane emissions from this sector were divided into four subsectors. The subsector values of CH_4 emissions are reported in

TABLE III-5 LANDFILL SOURCES OF CH4 EMISSIONS IN BC

	tonnes CH4 (1990)	tonnes CH4 (2005)
MSW	228,625	194,811
WOODWASTE	49,320	69,550
PULPWASTE	12,460	18,530
TOTAL	290,405	282,891

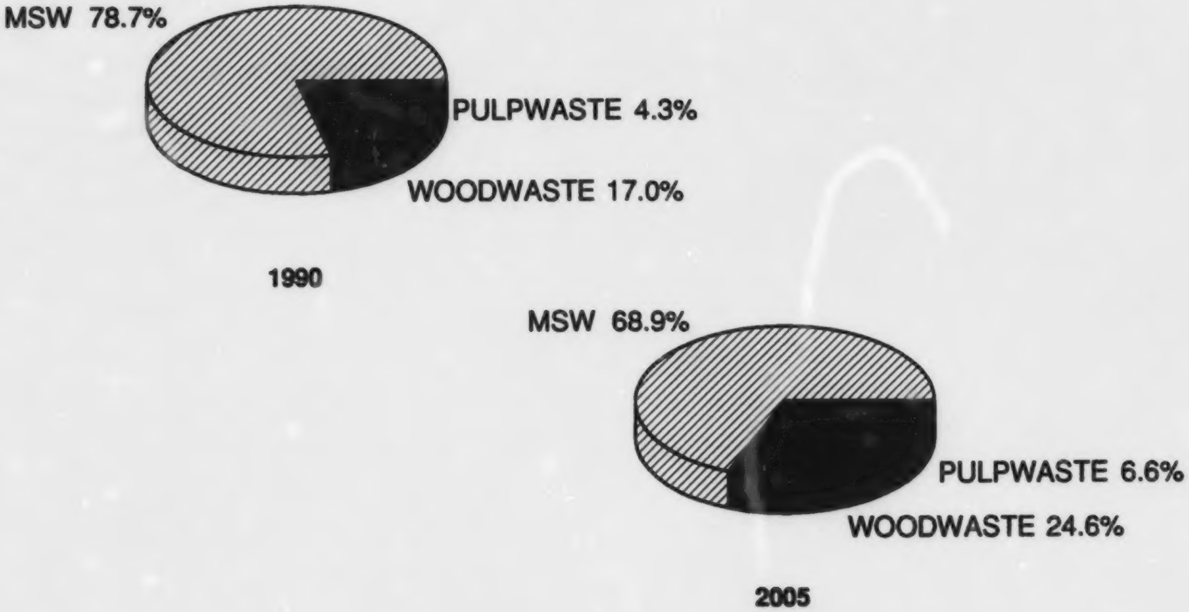


FIGURE III-4 LANDFILL SOURCES OF CH4 EMISSIONS IN BC

TABLE III-6 MANURE SOURCES OF CH4 EMISSIONS IN BC

	tonnes CH4 (1990)	tonnes CH4 (2005)
DAIRY CATTLE	44,326	57,926
BEEF CATTLE	2,146	2,888
OTHERS	11,843	11,843
TOTAL	58,315	72,657

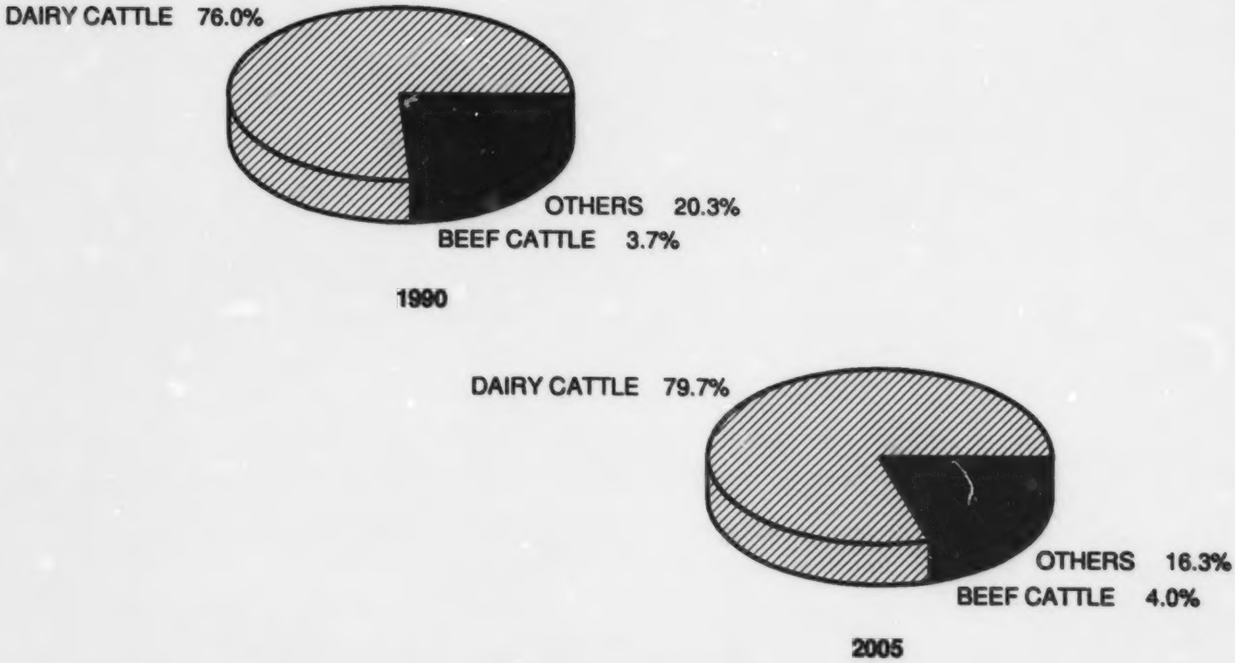


FIGURE III-5 MANURE SOURCES OF CH4 EMISSIONS IN BC

Table III-7 for 1990 and 2005. For 1990, 43,555 tonnes of CH_4 was emitted to the atmosphere from this source, making it the fourth largest emitter in B.C. Production and processing of natural gas are the largest sources of CH_4 emissions in this sector, accounting for 72% and 20% of the total in this sector, respectively, for 1990 (Figure III-6).

For the year 2005, all subsectors are expected to increase. CH_4 emissions from production of natural gas increases from 31,240 tonnes for 1990 to 54,886 tonnes for 2005. CH_4 emissions from processing of natural gas increases to 15,841 tonnes in 2005. This is an increase of 6,670 tonnes from the 1990 estimate of 8,811 tonnes CH_4. The contribution to the total anthropogenic emissions increase from 8% in 1990 to 14% in 2005 (Figures III-2 and III-3)

(d) Domestic Animals

The total CH_4 emissions from domestic animals in 1990 is 36,618 tonnes. Domestic animals are the fifth largest source in B.C. and amounts to 7% of the total 1990 anthropogenic sources. The emissions from the four main subsectors for 1990 and 2005 are reported in Table III-8. Beef and dairy cattle are the largest sources in this sector, accounting for 64% and 30%, respectively, for the year 1990. The "other" category includes sheep, goats, hogs, poultry and turkeys. Emissions from this sector are illustrated in Figure III-7.

Methane emissions from domestic animals are projected to increase by 16% from 1990 to 2005. The 42,427 tonnes CH_4 forecast for 2005 accounts for 8% of the total anthropogenic sources in that year. Beef cattle are expected to account for 61% of the domestic animal source emissions in 2005. This is down from 64% in 1990. Dairy cattle are expected to account for 34% of the domestic animal source emissions in 2005, up from 30% in 1990. Horses and other subsectors account for 3% each in 2005, similar to their 1990 values.

TABLE III-7 CH4 EMISSIONS FROM NATURAL GAS INDUSTRY IN BC

	tonnes CH4 (1990)	tonnes CH4 (2005)
PRODUCTION	31,240	54,886
PROCESSING	8,811	15,481
TRANSMISSION	2,154	3,792
DISTRIBUTION	1,350	2,378
TOTAL	43,555	76,537

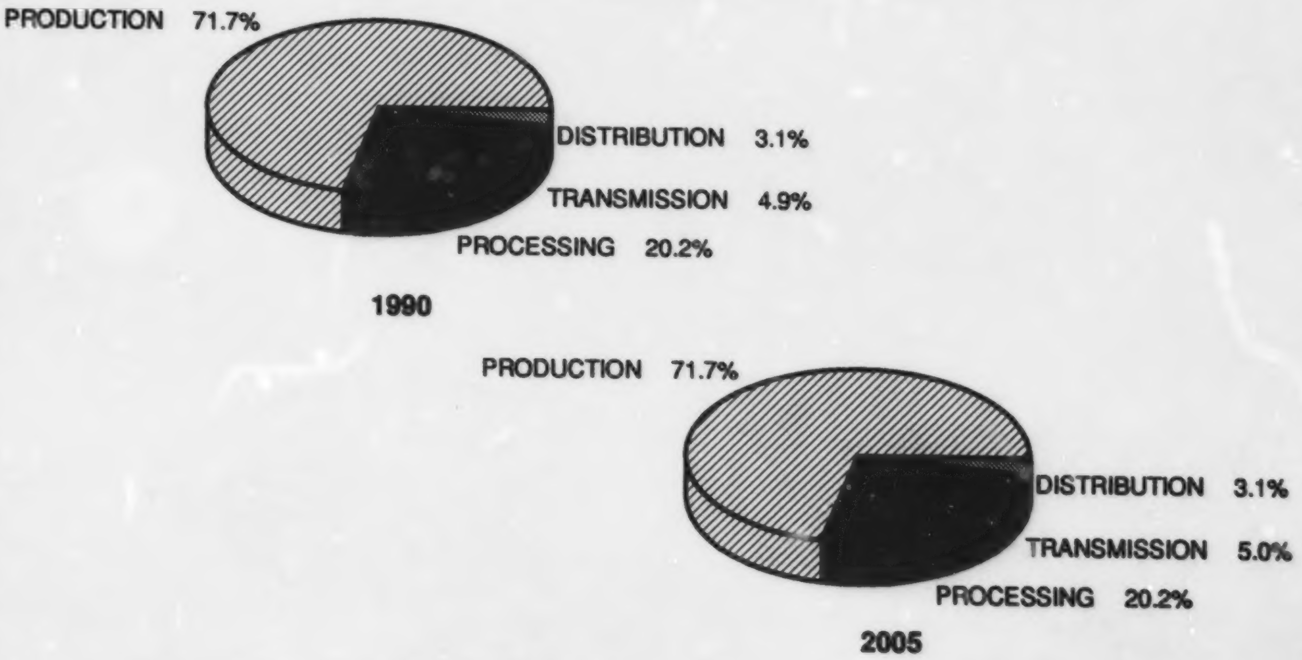


FIGURE III-6 CH4 EMISSIONS FROM NATURAL GAS INDUSTRY IN BC

TABLE III-8 DOMESTIC ANIMAL SOURCES OF CH4 IN BC

	tonnes CH4 (1990)	tonnes CH4 (2005)
BEEF CATTLE	23,399	25,738
HORSES	1,241	1,241
DAIRY CATTLE	10,877	14,214
OTHERS	1,101	1,233
TOTAL	36,618	42,427

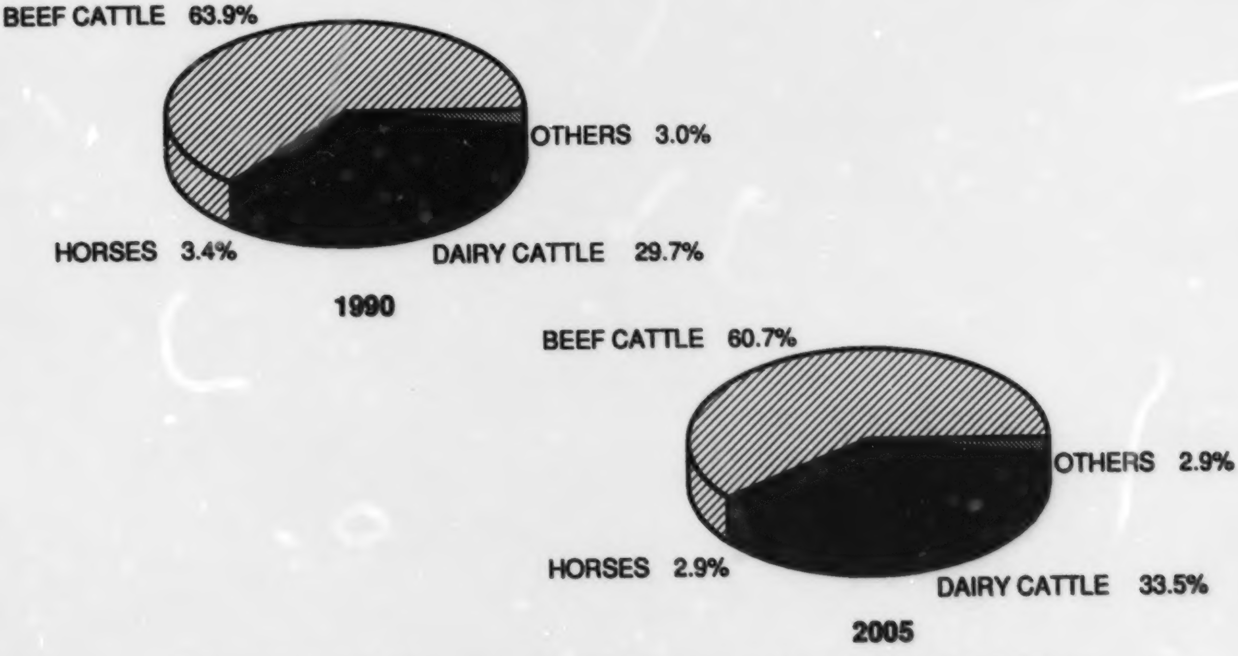


FIGURE III-7 DOMESTIC ANIMAL SOURCES OF CH4 IN BC

(e) Prescribed Fires

Prescribed burning is the sixth largest contributor of CH_4 emissions for 1990, totalling 17,736 tonnes. The forest management subsector is the largest, at 14,566 tonnes. These emissions are reported in Table III-9 and depicted in Figure III-8.

Prescribed fires will likely decrease by 30% by the year 2005. As a result of this, the share of the total CH_4 emissions from this sector will drop from 3% in 1990 to 2% in 2005.

(f) Oil Industry

Methane emissions from production and transportation of oil are given in Table III-10. In 1990, 17,288 tonnes of CH_4 were emitted from this sector. The majority of these emissions (99%) are associated with oil production.

For the year 2005, oil production is expected to decline, hence, CH_4 emission from this subsector is estimated to reduce to 6,871 tonnes. Emissions from the transportation subsector will remain approximately constant. The total emissions from this sector is 7,120 tonnes, which accounts for 1% of the total anthropogenic sources in B.C. for 2005. This is down from 3% in 1990. Figure III-9 illustrates emissions from each subsector for 1990 and 2005.

(g) Mobile Combustion Sources

Mobile combustion sources of CH_4 contributed about 2% of the total 1990 anthropogenic emissions or 8,991 tonnes. Emissions from five subsectors for 1990 and 2005 are given in Table III-11. Road vehicles account for 77% of the mobile combustion source emissions for 1990, while marine, air, off-road and rail account for 14.5%, 4.4%, 2.9% and 1%, respectively. Light duty gasoline vehicles contribute 64% of emissions for the road sector.

TABLE III-9 PRESCRIBED FIRE SOURCES OF CH4 EMISSIONS IN BC (1990)

	tonnes CH4
FOREST MANAGEMENT	14,566
RANGE/WILDLIFE	3,170
TOTAL	17,736

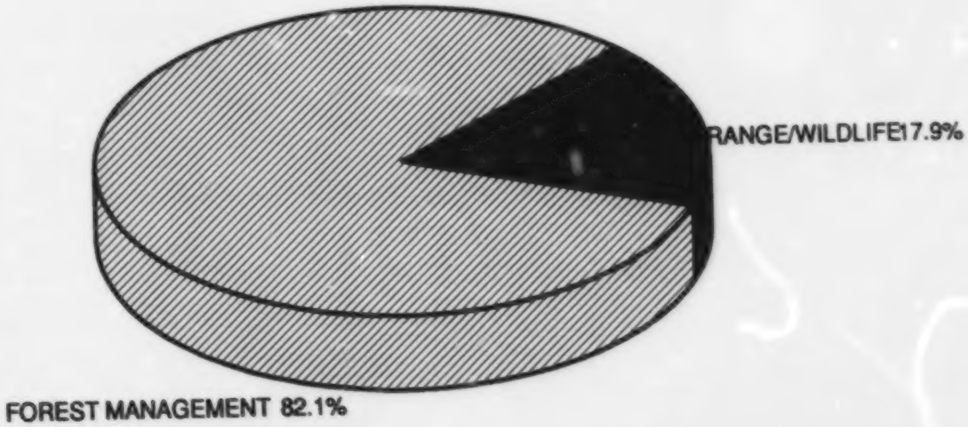


FIGURE III-8 PRESCRIBED FIRE SOURCES OF CH4 EMISSIONS IN BC (1990)

TABLE III-10 CH4 EMISSIONS FROM OIL INDUSTRY IN BC

	tonnes CH4 (1990)	tonnes CH4 (2005)
PRODUCTION	17,034	6,871
TRANSPORTATION	254	249
TOTAL	17,288	7,120

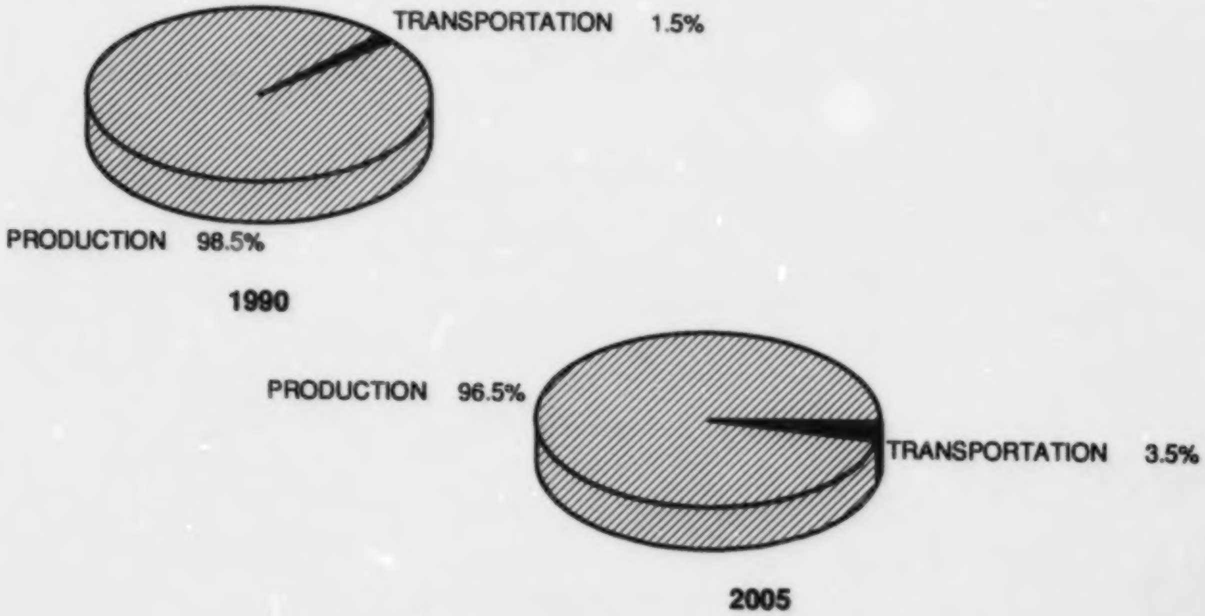
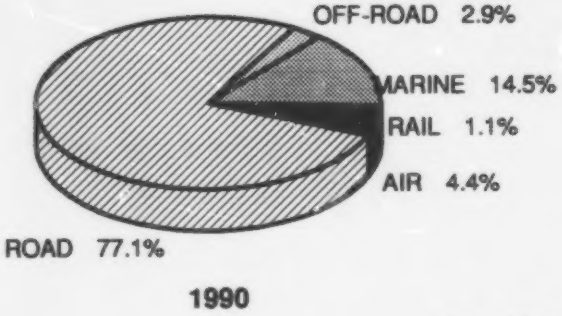


FIGURE III-9 CH4 EMISSIONS FROM OIL INDUSTRY IN BC

TABLE III-11 MOBILE COMBUSTION SOURCES OF CH4 IN BC

	tonnes CH4 (1990)	tonnes CH4 (2005)
ROAD	6,929	4,380
AIR	399	542
RAIL	102	107
MARINE	1,304	1,656
OFF-ROAD	257	257
TOTAL	8,991	7,392



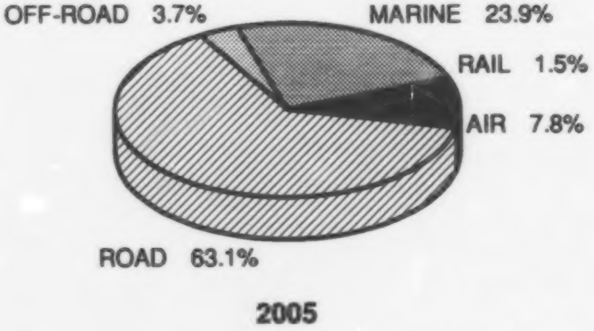


FIGURE iII-10 MOBILE COMBUSTION SOURCES OF CH4 IN BC

In 2005, mobile combustion sources will account for 1.3% of the total anthropogenic emissions, or 7,392 tonnes of CH_4. This is slightly lower than in 1990 as a result of improved pollution control equipment on vehicles in the future. Road vehicles are expected to account for 63% of the mobile combustion source emissions in 2005, down from 77% in 1990. The proportion from the marine subsector increases to 24% from 14% in 1990. Air, off-road and rail subsectors account for 8%, 4%, 1.5%, respectively.

Figure III-10 depicts emissions from the various subsectors for 1990 and 2005.

(h) Incineration

Emissions from this source account for 1.3% of the total anthropogenic CH_4 emissions in B.C. for 1990. Woodwaste incineration is the largest source in this sector and accounts for 99% of the 6,795 tonnes emitted by this sector (Table III-12). However, incineration of woodwaste using energy systems with more efficient combustion will reduce CH_4.

In 2005, incineration sources of CH_4 emissions in B.C. are expected to decline slightly due to alternate use of the Fraser River debris. Other subsectors are expected to remain the same.

Figure III-11 shows CH_4 emission sources from each subsector for 1990 and 2005.

(i) Stationary Combustion Sources

Stationary combustion sources are the smallest contributor of CH_4 emissions in British Columbia. 1,068 tonnes of CH_4 were emitted by this sector in 1990. The largest contributor of methane in this sector is the pulp and paper industry at 23% of the total stationary combustion source emission. Emissions from 13 subsectors are listed in Table III-13 for 1990 and Table III-14 for 2005. The second largest in this sector is the residential subsector. It accounts for 17% of the

TABLE III-12 INCINERATION SOURCES OF CH4 EMISSIONS IN BC

	tonnes CH4 (1990)	tonnes CH4 (2005)
MSW	54	54
WOODWASTE	6,699	6,699
FRASER DEBRIS	42	35
TOTAL	6,795	6,788

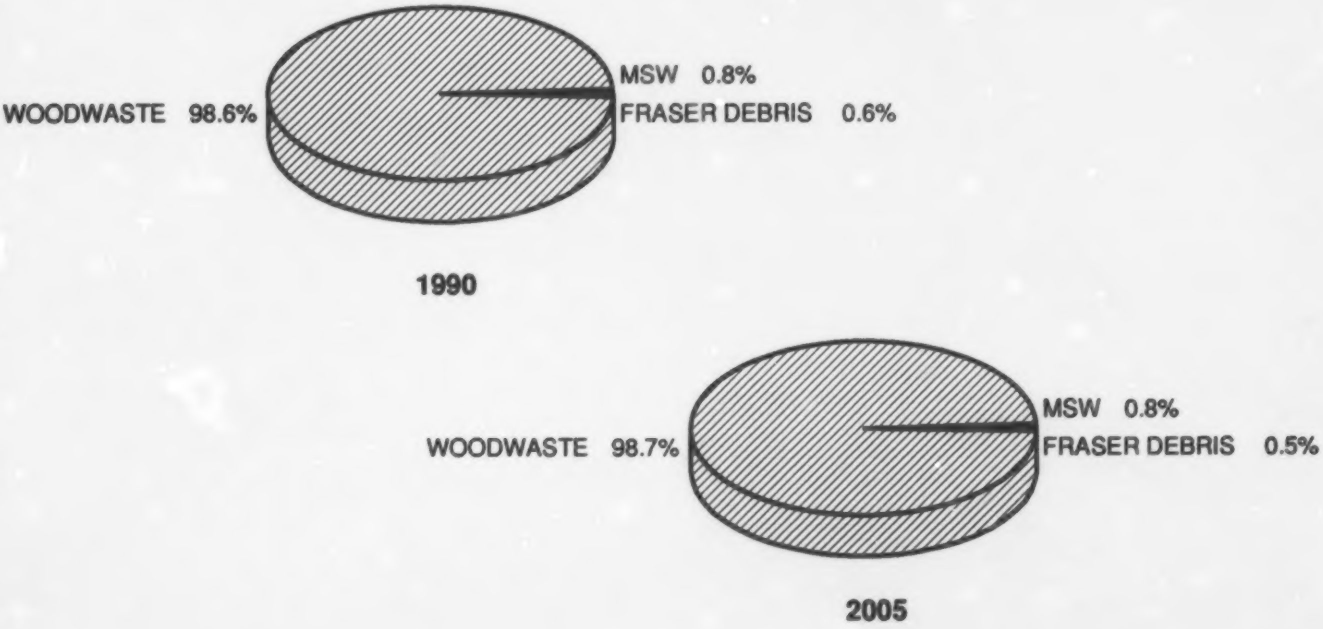


FIGURE III-11 INCINERATION SOURCES OF CH4 EMISSIONS IN BC

TABLE III-13 STATIONARY COMBUSTION SOURCES OF CH4 EMISSIONS IN BC (1990)

	tonnes CH4
INDUSTRIAL POWER	35
UTILITY POWER	2
RESIDENTIAL	186
CHEMICAL INDUSTRIES	6
COMMERCIAL	111
WOOD PRODUCTS	141
PRIMARY METALS	4
PULP & PAPER	246
NON-METALLIIC	6
PETROLEUM REFINING	42
MINING	97
OTHER MANUFACTURING	33
OTHER INDUSTRIES	159
TOTAL	1,068

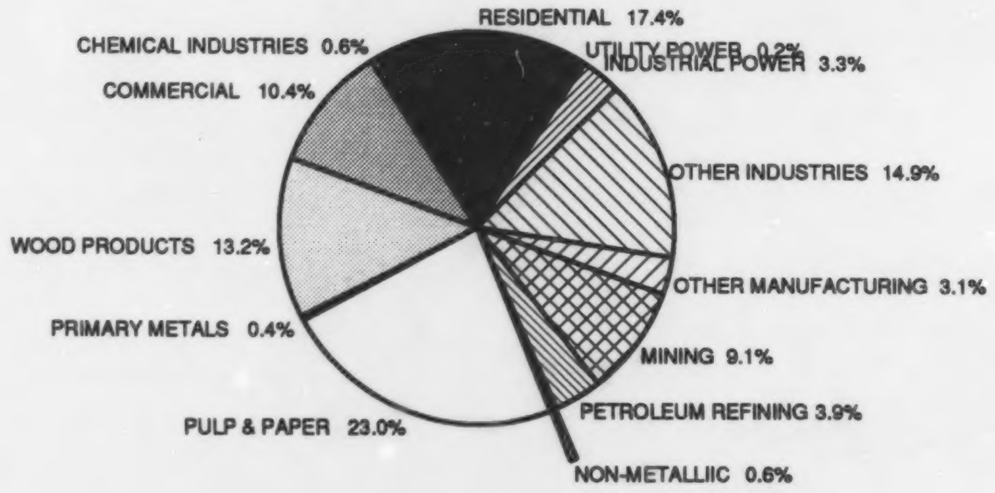


FIGURE III-12 STATIONARY COMBUSTION SOURCES OF CH4 EMISSIONS IN BC (1990)

TABLE III-14 STATIONARY COMBUSTION SOURCES OF CH4 EMISSIONS IN BC (2005)

	tonnes CH4
INDUSTRIAL POWER	94
UTILITY POWER	5
RESIDENTIAL	188
CHEMICAL INDUSTRIES	6
COMMERCIAL	124
WOOD PRODUCTS	132
PRIMARY METALS	3
PULP & PAPER	304
NON-METALLIIC	7
PETROLEUM REFINING	29
MINING	73
OTHER MANUFACTURING	53
OTHER INDUSTRIES	161
TOTAL	1,179

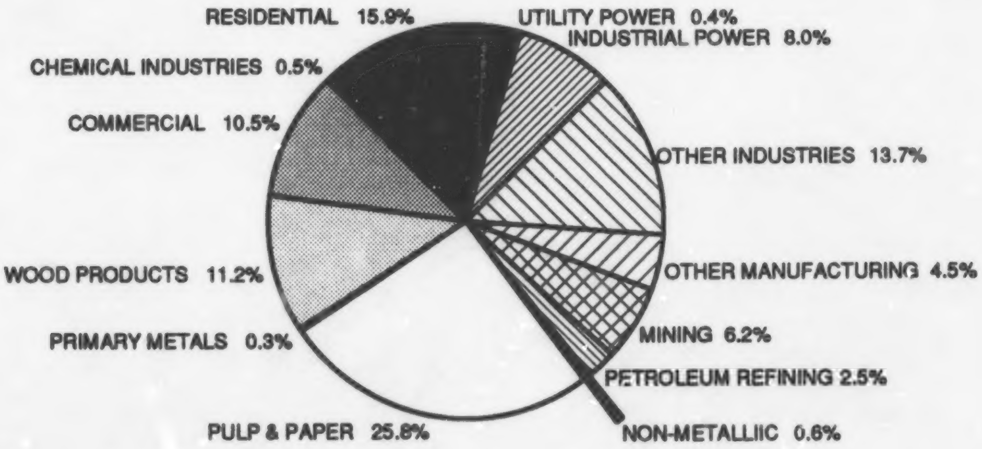


FIGURE III-13 STATIONARY COMBUSTION SOURCES OF CH4 EMISSIONS IN BC (2005)

total stationary combustion sources. Figure III-12 illustrates emissions from this sector for 1990 and Figure III-13 for 2005.

In 2005, 1,179 tonnes of CH_4 are emitted from this sector, slightly above 1990 emissions. Pulp and paper remains the largest, and residential the second largest in this sector.

2. Ranking of CH_4 Emissions

Methane emissions from natural and anthropogenic sources by order of rank are shown in Figure III-14 for 1990 and 2005.

In 1990, the top five sources accounted for 80% of the total CH_4 emission in B.C. Four of the top five sources are anthropogenic and account for 65% of the total emissions. Landfills were the largest source of methane emissions in B.C. for 1990.

For 2005, the top five sources are as in 1990, except for changes in relative position of the natural gas industry and manure sectors. The top four anthropogenic sources account for 74% of the total emissions, up from 65% in 1990. Landfills remain the largest source of methane emissions in 2005.

B. UPTAKE OF METHANE

1. Aerobic Soils

Recent studies have shown that aerobic soils are capable of consuming significant rates of methane (Table III-15). However aerobic soils generally contain both aerobic methane - consuming and anaerobic methane-producing microsites. It is the balance between production and consumption that determines whether an aerobic soil is a source or sink of atmospheric methane. Studies show that the organic-rich surface and wetter subsoil layers of aerobic soils can be net sources of methane emission (Sexstone and Mains, 1989; Yavitt et al., 1990).

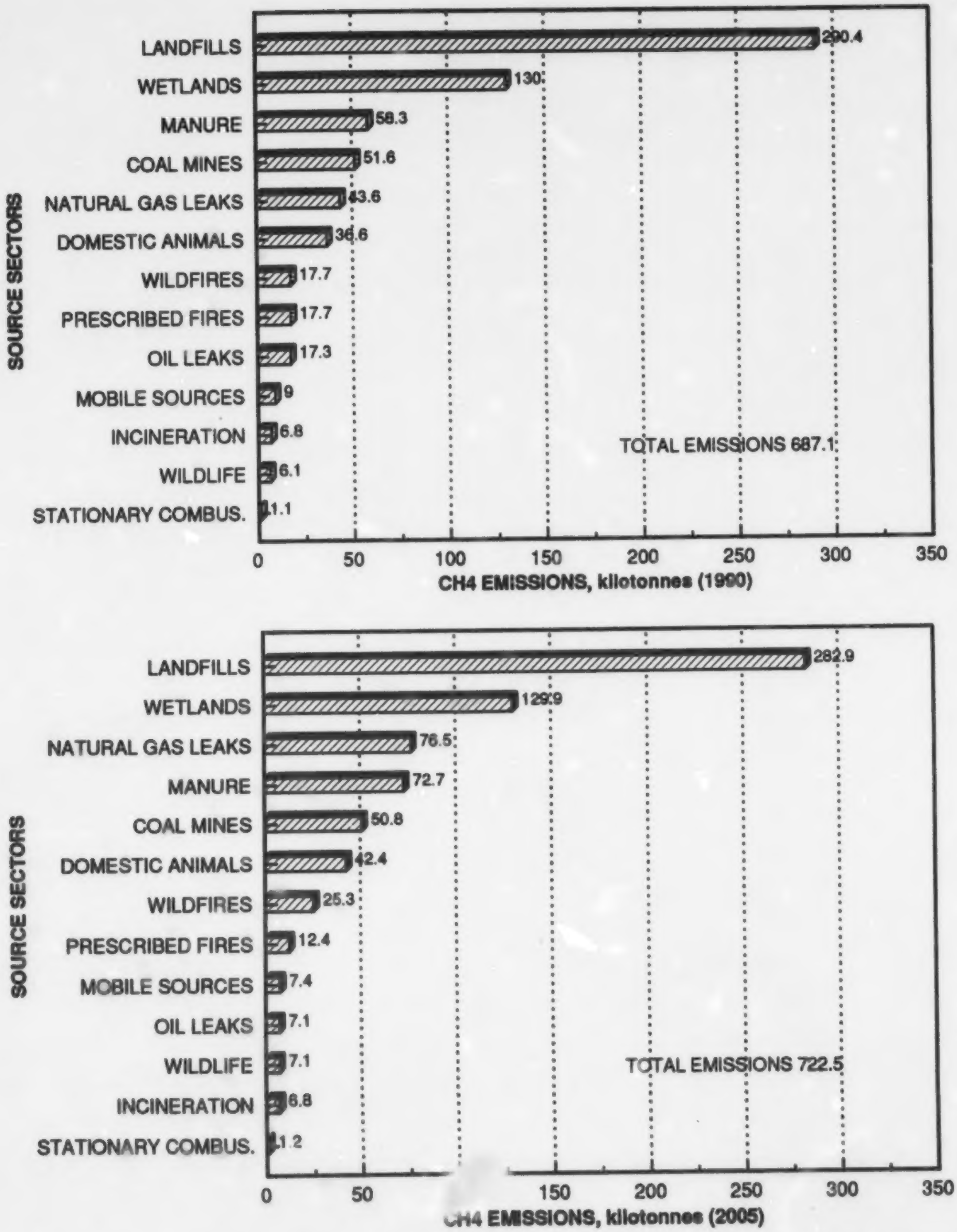


FIGURE III-14 CH4 EMISSIONS FROM ALL SOURCE SECTORS IN BC

TABLE III-15 A SUMMARY OF THE MEASUREMENTS OF METHANE UPTAKE BY AEROBIC SOILS

SOIL TYPE	METHANE CONSUMPTION mg m^{-2} d^{-1}	SOURCE
temperate forest soils	0.2	Keller et al., 1983
	4.2	Steudler et al., 1989
	0.6	Yavitt et al., 1990
tundra soils	0.6 - 1.2	King et al., 1989

Yavitt et al. (1990) found that the entire profile of the wetter of the two aerobic Appalachian forest soils they sampled was producing methane. Steudler et al., who measured a high methane consumption rate in a New England forest soil, found that methane uptake rates were decreased by increases in soil moisture and by nitrogen additions.

An additional unknown factor confounding the issue of methane consumption by aerobic soils is the role of soil fauna. According to Zimmerman et al. (1982), methane is generated in the guts of xylophagous (wood eating) insects. The best known example is termites. Measurements carried out in the tropics show that termites produce huge quantities of methane (Zimmerman et al., 1982; Rasmussen and Khalil, 1983).

Various authors consider aerobic soils as a small but significant sink in the global methane budget (Bouwman, 1989; Steudler et al. 1989; Nisbitt, unpublished). The category of aerobic soils covers a great variety of soil types, with a wide range of properties that will obviously cause considerable differences in the methane flux (for example, humid coastal podzols compared to soils in drier regions). Compared to soils in most of the world, B.C. soils are cooler, and have more surface litter, properties that are likely to reduce methane uptake.

The area of aerobic soils in B.C. is approximately 900,000 km^2 (Van Ryswyk et al., unpublished). Assuming that this cover consumes methane at an average rate of 0.6 mg m^{-2} d^{-1} for half the growing season (75 days), the net annual uptake for B.C. would be 41,000 tonnes (0.045 g m^{-2} yr^{-1}). Given the tentative exploratory nature of the published research, the error associated with this estimate is high, probably in excess of 200%. Research projects in Alaska and Central Canada are presently looking at methane uptake on a range of soils, and extrapolation from these data should be used to improve this estimate.

2. Atmospheric

Reaction with hydroxyl (OH) radicals in the troposphere is the predominant mechanism by which methane is removed from the atmosphere, affecting as well the atmospheric concentrations of ozone (O_3) and carbon dioxide (CO_2) (IPCC, 1990). Atmospheric sinks considered to be less significant are transport to the stratosphere (where reactions involving methane lead to the formation of H_2O), and reaction with chlorine (or other radicals) in the lower stratosphere or upper troposphere leading to the destruction of ozone.

By comparison to published methane budgets a rough estimate for the atmospheric sink over B.C. may be obtained. Prorating from the global estimate of 300,000 kt/yr (Bingemer and Crutzen, 1987; Bouwman, 1989), based on surface area, the approximate size of the sink for B.C. is 558 kt/yr. However, prorating from the more recent estimate for Oregon (Khalil and Shearer, 1990) gives a much higher estimate of 1130 kt/y. A more refined estimate requires consideration of local CH_4 and OH levels.

The OH concentration is dependent on a complex array of reactions with methane, carbon monoxide (CO), non-methane hydrocarbons (NMHC), nitrogen oxides (NO_x) and tropospheric ozone. Typically the lifetime of methane in the atmosphere is between 8 and 11.8 years, based on the reaction between CH_4 and OH, and is believed to have increased in the last century as the tropospheric levels of OH decreased in response to rising levels of CH_4, CO and NMHC (IPCC, 1990; Khalil and Rasmussen, 1985).

The role of methane in climate change has been discussed extensively in the literature, notably in IPCC, 1990; Rotmans and Swart, 1990; Bolin et al., 1986; Khalil and Rasmussen, 1985 and 1990; and Vaghjiani and Ravishankara, 1991. A simplified description of the chemistry is given by Manahan, 1984 and included in Appendix V.

The approach used by Khalil and Shearer (1990) in their estimate of the tropospheric sink for methane over Oregon was adopted for this study. In that model the sink is taken as the reaction of CH_4 with OH (which is the first step in the sequence that leads to the production of formaldehyde) within the troposphere over the area in question. Subdividing the domain into volume elements allows the calculation to be written as:

$$Q \propto K \; [OH] \; [CH_4] \; \Delta V,$$

where Q represents the sink (tonnes/yr), K the rate constant, [OH] and $[CH_4]$ the concentrations of OH and CH_4 respectively, and ΔV the volume element. The critical aspect of the model is to have reliable concentration data for CH_4 and OH as a function of latitude and altitude, and for each season.

The calculation of the sink over British Columbia was provided by Lu and Khalil (1991, see Appendix VI) based on their photochemical modelling results for the vertical and diurnal variation in OH levels, and data for CH_4. Estimates for the variation with latitude of OH levels were based on linear interpolations of data given in Spivakovsky et al., (1991), while for CH_4 these variations were predicted based on unpublished data (Khalil and Rasmussen, 1987), for Cape Meares (45°N) and Barrow (72°N). The rate constant was taken as the form provided in Demore et al., (1985) for NASA, as noted in Lu and Khalil (1991) (Appendix VI).

Three test runs were performed to test the sensitivity of the model to the number of areal sub-domains assumed; one run was done sub-dividing B.C. into six sub-areas (by latitude), one using two subdivisions, and one treating B.C. as simply one domain. The results were not substantially different, so the results used were from the intermediate run (2 sub-divisions, vertical profiles of OH and CH_4 calculated at 48°N, 54°N and 60°N).

Approximately 490 kt/year, with minimum and maximum values of 390 and 610 kt/year, of methane are oxidized in the atmosphere in B.C.

Recent re-evaluation (Vaghjiani and Ravishankara, 1991) of the magnitude of the rate constant in the CH_4 - OH reaction would, if incorporated into the Lu and Khalil model, drop the estimate for the sink by only approximately 10% (Khalil, 1991). Thus, the refined calculation for the annual atmospheric methane sink over B.C. is in the range of 350 to 550 kt, with 440 kt being the best estimate.

Transport of methane to the stratosphere may be assumed proportional to methane level, for which a rough estimate for transport velocity may be taken as 0.015/year (Rotmans and Swart, 1990).

Using a simplistic approach, transport to the stratosphere would represent less than 20% of the magnitude of the sink by oxidation. Because of the uncertainty and complexity of this transport process, this additional potential sink was not incorporated into the final estimate.

C. ESTIMATE OF ERROR

Uncertainty exists in any estimates made of emissions of pollutants as with estimates of any randomly varying quantity. The uncertainty in estimates of air emissions has two components, these being precision uncertainty and bias uncertainty (Horie et al., 1988). Precision uncertainty refers to the error in estimating the mean of a random variable. Bias uncertainty reflects the inaccuracy of the estimated mean from the true value, which is seldom known. Bias arises due to systematic errors in the estimation methodology, which may lead to over or under-estimation of the true value, that cannot readily be determined because no direct measurements of the random variable are available.

To estimate precision uncertainty in the 1990 methane emissions inventory for the anthropogenic sources staff engineers familiar with inventories provided estimates of uncertainty for each category. The individual error estimates were applied to each category throughout the inventory to arrive at the standard error calculated by the equation:

$$\varepsilon_T = \frac{\sqrt{\sum_{i=1}^{n} (\varepsilon_i E_i)^2}}{E_T}$$

where ε_i = relative uncertainty in each emission estimate

ε_T = overall relative error

E_i = emission estimate for each category

E_T = overall emission estimate

For a more detailed discussion of the methodology used to calculated error, the reader may refer to the GVRD Air Management Plan - Stage 1: Appendix A5 Current and Future Emissions, (Edwards and Lee, 1989).

The composite uncertainty in total anthropogenic methane emissions in B.C. for 1990 was calculated to be 19% or (532 ± 100) kt.

This estimate is probably reflective of the error in the overall inventory. The error in the emission estimates for individual subsectors should be higher, depending on the accuracy of the base quantity and emission factor used.

IV. CONTROL MEASURES

A. MASTER LIST OF CONTROL MEASURES

For each sector and subsector of the inventory, several methane emission mitigation measures were identified and ranked qualitatively on the basis of perceived technically achievable emission reduction potential, cost, ease of implementation, state of development of the technology (i.e. proven, emerging, unknown), and the time frame for implementation of the control measure. Technology based controls as well as economic and other incentives were considered. A complete listing of all identified measures is given in Appendix VII.

There are too many possible control measures for all to be analyzed quantitatively in this study. Consequently, control measures were chosen selectively from the master list for more detailed analysis. These were selected for the major source sectors and subsectors, with consideration of their potential technical and economic viability.

B. ANALYZED SHORT-LISTED CONTROL MEASURES

The top emitters identified in the inventory for anthropogenic emissions were selected for further review of potential controls. Anthropogenic sources in 1990 accounted for more than three-quarters of the total (anthropogenic and natural) emissions within the province, and of those the top four emitters (landfills, oil and gas, coal mining, and manure) contributed over 80%. Case studies were consequently selected for each of these source sectors. Rather than cover the entire oil and gas industry, only gas production is reviewed, as it is the predominant source within that sector. Additionally, the merits of economic incentives and other similar measures, as well as control measures for mobile sources are also discussed in this section.

1. Landfill Gas Recovery

(a) Description

Broader application of currently available landfill gas recovery technology is the most cost-effective control measure identified for anthropogenic sources of methane in British Columbia. Of the six known largest MSW landfills in B.C. (all are over 1.5 million tonnes of MSW in place), three have gas recovery systems scheduled for startup this year and three have some form of gas recovery/flaring system already in place. None of the identified sites containing under 1 million tonnes MSW in place currently have control systems. By contrast suggested NMOC control measures in California target landfills which have 500,000 tons (454,000 tonnes), or more, of waste in-place (California Energy Commission, 1991), and the U.S. EPA recently proposed standards and guidelines addressing gas recovery systems for landfills which contain 100,000 tonnes of waste or more and which are predicted to emit 150 tonnes of NMOC annually (JAWMA, 1991; EPA, 1991). The EPA action was prompted by concerns over air emissions from landfills which contribute to ambient ozone problems, air toxic, global warming, odour nuisance and potential explosion hazards.

Landfills are sources of methane and carbon dioxide (greenhouse gases, with methane being the more potent of the two) as well as, in small concentrations, toxic air pollutants (e.g. vinyl chloride, benzene, carbon tetrachloride, chloroform, trichloroethylene etc), ozone precursors (non-methane organic compounds) and odorous gases such as alcohols, esters and mercaptan (California Energy Commission, 1991). Burning the gas recovered from a landfill not only reduces emissions of methane (converting it mostly to CO_2) but also tends to mitigate these other concerns. The presence of vinyl chloride in landfill gas may be cause for the California "Suggested Control Measure" now proposed with a limit of 500,000 tonnes to be applied to landfills of all sizes (California Energy Commission, 1991).

In addition to gas recovery, other control measures for landfill emissions include recycling and reduction of waste going to landfills, incineration, converting MSW to energy, and composting. Currently, separate initiatives are underway, with MSW deposited to landfills in B.C. targeted for a reduction of 50% by the year 2000 through recycling and source reduction programs, and energy-from-waste technologies under review in a study being conducted by Levelton Associates (1991). The third option, composting programs, generally requires sorting of the waste stream and therefore in practice may be combined with a recycling program, and may be feasible depending on tipping fees and/or sales of refuse-derived fuel (RDF) and/or compost.

Gas recovery was selected for review. A landfill gas recovery system should (EPA CFR, 1990):

- be sized to handle the maximum gas generation rate;
- have a design allowing for monitoring and adjustments in the operation of the system;
- collect gas from all areas of the landfill that warrant control;
- have a design allowing for expansion of the gas recovery system as the landfill grows;

and

- be operated over their entire useful life (15 years approx.).

An open flame capable of reducing emissions of non-methane organic compounds (NMOCs) by 98 weight percent was specified in the EPA's proposed guideline as the best demonstrated technology, although particular systems may in addition have energy recovery schemes as economic conditions dictate.

(b) Capital and Operating Costs

Cost estimates for landfill gas recovery systems are sensitive to site or project specific parameters such as the methane generation rate and its controlling factors; gas processing requirements, which depend on the end-use or market for the gas; and any existing or pending environmental or other regulation which affects the design, construction or operation of landfills and/or gas recovery systems. This case study considers a landfill gas recovery system for an active landfill 10 metres in depth containing 450,000 tonnes of MSW to which 50,000 tonnes are added annually.

Sales of the medium grade gas as is (approximately 25 MJ/m^3 or 540 BTU/SCF) or after upgrading (at additional costs) to pipeline quality gas (which is roughly 95% CH_4 and 38.4 MJ/m^3 or 1030 BTU/SCF) would offset the costs of the gas recovery system. Additional costs would be expected for processing and the pipeline to deliver the gas to market. However, securing a market for the relatively small amount of gas from landfills (under 1 million tonnes of MSW) such as considered here may be difficult and is not expected ordinarily. If markets were obtained, the upgraded gas option may be preferable based on the analysis of the options for California (California Energy Commission, 1991) collect and flare; sell medium grade gas, and upgrade to high grade gas and sell. Only the last was considered to have economic benefits which exceed costs, based on assumed gas prices of U.S. $1.24 and U.S. $4.41 per Mcf, respectively, for medium and high grade gas.

A landfill gas recovery system operated locally more probably would obtain a contract price in the range of only $1.50 to $1.75 per Mcf ($1.40 - $1.60/GJ) for pipeline quality (high BTU) gas.

For the purposes of estimating capital costs, one well is assumed for every 2.5 hectares (one acre) to adequately recover gas from the site. For the 450,000 tonne site, approximately 18 vertical wells would be required initially. Adding 50,000 tonnes of MSW annually means that over 10 years another 18 wells would be required, bringing the total to 36 wells. An annual maintenance cost is allotted for the additional wells, associated header pipe and other equipment. The capacity of the landfill is assumed to not be reached in this time.

The capital cost breakdown is as follows:

Capital Costs	$000
Extraction Wells (7.6 m/25 ft deep) $8000/well x 18	108
Blowers (2; 1 as backup)	40
Electrical and Controls	40
Flare	70
Header Pipe (1200 m @ $110/m; 4" - 8" diameter, above ground)	132
Enclosure for flare/blower station	27
Portable Flame Ionization Detector	10
Subtotal: Material and Installation	**427**
Engineering and Permitting (15% of Capital)	64
Subtotal: Capital	**491**
Contingency (20%)	98
Total Capital:	**589**
Capital Recovery (10 yrs @ 15%) ($000/yr)	117

Operating costs are estimated as follows:

Operating Costs	$000/yr
Labour:	
Administration, Operating and Maintenance	50
Contract Maintenance (3% of Capital)	18

Operating Costs - Continued	**$000/yr**
Maintenance Materials (4% of Capital)	24
Energy:	
Electricity ($0.05/kwh x 20 kw x 24 x 365 h)	10
Propane	5
Insurance & Local Taxes (1% of Capital)	6
Subtotal Operating:	**113**
Contingency Operating (20%)	23
Total Operating:	**136**
TOTAL CAPITAL AND OPERATING: ($000/yr)	**253**

The operating costs were estimated assuming the local municipal government runs the gas recovery system. If the recovery system is instead operated privately then an additional allowance must be made for the contractor's charges for administration, engineering, overhead and profit.

(c) Emission Reduction and Cost-effectiveness

It is assumed that the landfill gas recovery system will collect 50% of the gas and this gas is combusted at 98% efficiency. Higher collection efficiencies are possible but are not assumed here, and in any case, tend to produce gas of lower heating value.

Following the approach used in the national inventory (El Rayes and Edwards, 1991), the EPA model for estimating emissions from landfills was used to obtain an estimate for the methane generated by the 450,000 tonne landfill considered in this case study. The default values for k (0.02 yr^{-1}), L_o (8120 ft^3/tonne refuse) and composition (50% CH_4, 50% CO_2) were assumed. Then to approximate the growth of the landfill, the amount of refuse in place in the landfill was taken as 25,000 tonnes in the first year and subsequently to grow by 50,000 tonnes each year. In the tenth year of operation it reached 450,000 tonnes at which point the gas recovery system was assumed installed. The amount of methane generated in the following ten years of operation as calculated by the model was 18,222 tonnes.

The gas recovered in each year of the ten-year operation was taken as 50% of the total gas recovered in that time (18,222/2, or 9,111 tonnes) uniformly distributed over the 10 years, or 911 tonnes each year. Assuming a 98% combustion efficiency then gives an estimated 893 tonnes of methane emission reduction annually.

The cost-effectiveness, excluding any revenue from gas sales, is then the total annual capital and operating costs of $253,000 over the emission reduction of 893 tonnes, or $280/tonne. Costs would be higher if the project is operated privately but may be offset if a market can be secured for the gas, or monetary value is assigned to the benefits of the reduction of air toxics, NMOC emissions and odour nuisance. If all of the collected gas is sold at a price of $1.40/GJ, the revenue generated would be $70,800/yr. This offsets some of the cost of the system and reduces the cost to $200/tonne methane reduction.

(d) Other Benefits and Impacts

The added benefits of limiting problems with odour and reducing emissions of toxics and ozone precursors (NMOC) in addition to the control of methane releases are in themselves incentives to install landfill gas recovery systems on all suitable sites. However, a number of adverse effects as well as other beneficial aspects are associated with these systems (Schumacher, 1983) and these are discussed below.

Among the other beneficial aspects are:

- reduction or prevention of methane accumulation around the general area of the landfill which otherwise can present a fire or explosion hazard;
- enhancement of environment around or near the site;
- potential source of alternative energy (low carbon fuel), which if utilized will displace some existing energy supply;
- reduces odour nuisance;

and

- reduces NMOC and toxic emissions, which contribute to ozone formation and some of which are known or suspected carcinogens or cause non-cancer health effects.

Adverse effects of landfill gas recovery systems include:

- odour from wells and material moved from the wells, and from the gas collection and processing systems, especially during downtime. These odours would be lessened by the gas recovery system but not eliminated;
- NO_x emissions (ozone precursor) from compressors, engines, flares and other equipment;
- noise from compressors and other processing equipment;
- nuisance light source;

and

- leachate and condensate problems are common. Costs may increase dramatically if the condensate is prevented (by regulation) from being returned to the landfill.

2. Manure Treatment

a) Description

Methane from manure can be reduced using either anaerobic or aerobic processes. Aerobic digestion was chosen for a case study over anaerobic because it is believed currently to represent a more practical means of manure treatment for small and medium-sized farms. However, a discussion of anaerobic systems is given here for purposes of comparison.

Anaerobic systems tend to have problems with corrosion (biogas is corrosive), process upsets (methanogenic bacteria in the digesters may die if the ambient temperature drops too low e.g. to 10°C, or if disinfectant and/or antibiotics get into the digester); downtime (from equipment failures for gas metering, relief valve, heat exchanger etc.) for which the farmer often would not have the time or the know-how to fix) required high skill level of the operator; and have long startup periods (Van Die, 1987 and P. Comm., 1991; Prairie et al., 1987; Stickney, 1991). Costs potentially may be recovered for anaerobic systems either by revenue from gas sales (for which gas cleanup is necessary) or the displacement of energy otherwise purchased for farm operations. Centralized facilities taking manure from several operations would have additional costs for trucking, which tend to negate advantages associated with economies of scale.

Costs for an anaerobic system equipped with electrical cogeneration facilities were estimated (Prairie et al., 1987) for a 300 cow dairy operation in Ontario. Total manure production was taken as

17.1 m^3/d. The digester was sized at 500 m^3 (9.2 m diam. and 8.5 m ht). The annual biogas energy production was estimated as roughly 2600 GJ, fuelling a 30 kW cogeneration unit to produce 200,000 kwh/yr. Most of the recoverable energy (1200 GJ/yr) was used for the digester, leaving roughly 100 GJ/yr for other applications. The total capital cost was estimated at $340,000 (updated from 1987 dollars using the Marshall & Swift equipment cost indices, as 928.6/813.6 of the 1987 cost), which amortized over 20 years at 15% is a $54,300 annual cost. The operating and maintenance cost would be about $4,400/yr. Revenue from electricity sales, or displaced cost, would total roughly $10,000/yr., assuming $0.05 per kwh sold. The net annual cost would be approximately $48,700 or $1,000/tonne methane reduction.

Experience with aerobic and anaerobic systems has shown that aerobic systems are preferred for small farm operations since they are simpler for the farmer to maintain and operate. Aerobic treatment systems can work with lagoons or tanks. Lagoons are a lower cost alternative, but usually are operated allowing varying depths of fill, which makes it more difficult to ensure that adequate mixing (aeration) is maintained. Generally, poorer mixing is obtained as the level of fill drops. Tanks filled to constant depth from a collection pit avoid this problem. The design and cost estimate for an aerobic digestion system (that uses tanks) given below were based on recommendations from one local supplier.

For the cost estimate, a 200 cow dairy farm was assumed as dairy operations were the largest contributors to methane emissions from manure production in B.C. Manure handling facilities (daily collection pit and lagoon) are taken to be in-place.

Daily manure production is pumped from the collection pit to a continuous flow aerobic digester for treatment for seven days prior to discharge to the farm lagoon. A 200 cow farm producing 14.7 tonnes daily of 14% solids manure (or a 200 sow hog farm producing

16.6 tonnes of 13% solids manure) would require two 6 meter diameter by 5 meter height tanks equipped with aeration diffuser manifolds on their bottoms. Both manifolds would be connected to a single 10 hp air blower which would supply air to the manifold. The supernatant would be discharged to the farm lagoon by gravity. Maintenance requirements would consist of lubricating the air blower once a month at an estimated time requirement of one half hour per month, as well as routine inspection and repair of other parts of the system.

b) Capital and Operating Costs

Annual cost estimates for an aerobic digestion system based on typical costs provided by Sanitherm Engineering (p.comm., 1991) are as follows:

Capital Cost	$ 000
Aeration Tanks (2) (6m Ø x 5 m ht.) ($ 45,000. ea.)	90
Cement Slabs (2) ($1500 each)	3
Air Blower (10 HP/7.5 kw)	8
Air Diffusers Pipes and Valves	5
Miscellaneous	4
Subtotal (Equipment)	110
Installation (40% of equipment costs)	44
Subtotal (Capital)	154
Capital Recovery (15 years @ 15%) ($000/yr)	26.3

Additional site-specific items are assumed to be covered by the contingency allowance (below).

Operating Cost	$000/yr
Power 7.5 kw x $0.05/kwh x 24 x 365	3.3
Labour (Daily Check) 0.5h/d, 365 x $15/hr	2.7
Miscellaneous (Oil, etc)	0.6
Subtotal (Operating)	6.1

Subtotal (Annual Operating and Capital) ($000/yr)	32.4
Contingency (25%)	8.1
Total Annualized Cost: ($000/yr)	**40.5**

c) Emission Reduction and Cost-Effectiveness

From a daily manure production of 14.7 tonnes, assuming 0.186 tonnes of methane are produced per tonne of volatile solids where the amount of volatile solids is taken as 11.63% of the total manure production, over a 365 day period an estimated 116 tonnes of methane may be generated and released to the atmosphere.

Although the exact figure under B.C. conditions is not known it is estimated that aeration for seven days could reduce methane emissions by at least 70% (Czerkawski and Breckenridge, 1969b). Further, it has been shown that aeration for only two days has reduced the odour producing volatile solids of hog manure by 32% (Van Kleek, 1991 Personal Communication) without reducing the amount and value of the fertilizer minerals potassium and phosphorus.

Applying the 70% reduction estimate to the 116 tonnes/yr emission estimate for the 200 cow dairy farm gives an annual emission reduction of roughly 80 tonnes for the aerobic digestion system.

The cost-effectiveness of the aerobic digestion system is then the $40,500 annual cost over the 80 tonne annual reduction in methane emissions, or roughly $500/tonne.

d) Other Benefits and Impacts

Odours associated with the manure from the dairy (or hog) farm would be reduced.

Potentially air and water quality impacts from untreated manure will be decreased.

3. Degasification of Coal Mines

a) Description

Although coal mines were found collectively to be one of the largest anthropogenic sources of methane in the Province, most in B.C. are surface operations which typically represent uneconomic prospects for coal bed methane (CBM) recovery. The description of the recovery scheme, estimation of emission reduction and cost estimate given here for degasification of a surface seam are based upon a number of assumptions rather than specific case studies from the literature or industry because of the lack of data from any recovery systems in the Province.

In surface mining methane emissions are attributed to the mined coal fragments as well as the exposed faces of the coal seams. Surface mines have both in abundance, due to typically high daily production and vast areas of exposed surfaces. Methane emissions assigned to the coal fragments represent roughly one-sixth to one-third of the total emissions for surface coal mining in B.C. (Hollingshead, 1990). As well, high rates of methane emissions may occur for short periods of time during blasting operations, as the coal seams are disturbed, but no estimate is available for the total methane released from those events.

Coals in western Canada (e.g. Western bituminous, medium-low volatile) are considered friable (hence potentially more permeable) and lose their methane quickly once handled, as do coals that have been tectonically sheared - e.g. as in the western Canadian foothills and mountains. Friable coals lose 90% or more of their methane during or before mining (Hollingshead, 1990). Coal therefore located at or near the surface in B.C. is assumed to have degassed to some extent, leaving a low residual methane content, and is considered to show little potential for methane recovery.

Parties interested in coal bed methane recovery in B.C. may review in detail current operations in Europe and the U.S.A. - e.g. the San Juan Basin Project in New Mexico. In general, CBM projects involving underground coal seams are considered more feasible than those for surface mines, and in some cases are justified on a stand-alone basis (i.e. - independent of revenue from coal mining). Degasification prior to mining an underground seam has dual added benefits relative to surface mines in that both an increased level of safety is realized and ventilation costs are reduced in subsequent mining operations, due to the resulting lower ambient methane levels in the mine. Horizontal wells undergoing tests currently may further improve the economics for this type of degasification.

CBM recovery projects outside of B.C. may have advantages relative to any within the Province in that water disposal may not be an issue (most likely it will be in B.C. due to high dissolved solids levels expected for the produced water) and alternative energy development credits (government grants) may be available (not expected to be the case for B.C.) (MEMPR, 1991).

In any case, implementation of economic CBM recovery projects in B.C. will require detailed site-specific feasibility studies. These studies would also determine the practicality of having gas wells and coal mining operations together on the particular sites in question. No such studies are available for British Columbia as interest shown by industry has not extended to recovering gas from existing surface mines, which are the predominant source of methane emissions coal mining in B.C.

Reducing methane emissions from surface mines is a global problem, as many (especially the developing) countries are expected to rely on surface coal deposits for their growing economies as a cheap source of energy (IPCC, 1990; Kirchgessner, 1991). Limiting greenhouse gas emissions from this source is the subject of on-going research by the U.S. EPA and others. Degasification of surface coal beds, and piping the gas to market, may well prove more economic than mining coal for countries that do not have coal transport infrastructure (e.g. rail lines) in place now.

b) Capital and Operating Costs

Costs for drilling a well for CBM recovery typically are higher than for drilling a conventional gas well under the same circumstances, but are comparable. Outlays of up to $350,000 to $400,000 per well (1000 metres in depth) for CBM would be expected, which would include costs for surface facilities and a tie-in to a transmission line (Nikols, 1991; Hobbs, 1991). A conventional gas well, (e.g. 1500 metres in depth) would cost closer to $300,000.

Wells to this depth would not ordinarily be operated to drain methane from surface coal seams, and in practice would not necessarily even be located where there are surface coal deposits since it is the deeper coal seams which are targeted as the prime CBM resource.

An order-of-magnitude budget cost estimate was prepared (based on discussions with Wilford, 1991) for coal gas recovery from one section of a generic surface mine. It was assumed that the mine was in operation, or was in the planning stage, so that roads, bridges, (some) water disposal facilities, and buildings are all in place or can be charged against the mine. Water disposal can be a problem in CBM recovery, but no further allowance was made here other than what would be available typically at a mine site since, if there was a problem, the solution would be site-specific and its costs difficult to predict. It was also assumed that the capital recovery period was three years, allowing degasification only until mining begins. No salvage value was assumed for the equipment, to be conservative in the cost estimate.

Well depths would range from 200 to 600 feet, so an average of 400 feet was assumed. Well spacing should be denser than for conventional gas reservoirs and was set to 40 acres over one section (approximately one square mile) for a total of 16 wells. Each well is assumed to produce gas at an average rate of 60 Mcf (1700 m^3) per day, which is used on site for heating or drying. If the gas is of sufficient quality it may instead be sold for roughly $1.50 to $1.75/Mcf but the price depends on proximity, to markets and competitive gas supplies. The mine itself would be the logical user, with fuel demands for heating and heavy duty vehicles. All pipelines would be buried to allow for winter operations.

The capital cost allowing for drilling, completion, pipelines and surface facilities (gas water separators, flare with a knockout tank, compressor etc.) was estimated at roughly $3 million. Assuming capital recovery over 3 years at 15% gives an annualized cost of $1.3 million.

Operating costs were estimated as roughly $350,000 per year, allowing $12,000 per well for labour, 4% of capital for maintenance and 100 kW power usage at $0.05 per kwh. Annual taxes and insurance were taken as 1% of capital.

The total annualized cost was estimated to be $2.1 million. If the capital recovery period was taken as 10 years, the total annualized cost would drop to roughly $1.1 million, or $67,000 per well.

Significant cost reductions may be achieved through the use of surface lines (rather than buried), less expensive drilling and completion technology, and by considering salvage value and the value of water drainage to subsequent mining operations (CH_4 International, 1991); wells may be installed for as little as $20,000 each (annualized operating and maintenance cost, over 10 years). The cost of demethanation decrease if coal mining operations allow longer lead times for CBM recovery. Shutdowns in winter may be necessary at times.

c) Emission Reduction and Cost-effectiveness

The degasification facility is assumed to run three years at which time mining operations commence and degasification ceases. Ultimately 50% or more of the gas in place could be recovered but typically only over five to twenty, or more, years. Higher rates of degasification could be obtained in the first three years by increasing the number of wells (decreasing the well spacing) and increasing the production rates, but at increased capital cost.

In the first six months, or longer, water production is expected to dominate. Gas production rises after that time. An average calendar day production rate of 1700 m^3 (60 mcf) per day per well is assumed over the three year period for a total gas recovery for 16 wells of 30 million m^3, or roughly 7000 tonnes of methane per year.

A comparison of the amount of gas recovered by degasification to that expected to be in place may be made as follows. Assuming 20 metres of coal are in the section drilled, with each tonne of coal containing 2 kg of methane that may be released, and the coal and CBM gas densities respectively are 1400 and 0.7 kg/m^3, leads to an estimate of 210 million m^3 of gas in place initially. The 10 million m^3 recovered in each year of the (3 year) degasification program then represents under 5% of the gas-in-place.

The cost-effectiveness, excluding the revenue from recovered methane, is taken as the $2,100,000 annual cost over the amount of CBM recovered in one year, 7000 tonnes, or $300 per tonne. This number may be expected to vary principally with the geological characteristics of each site, production methods, well spacing and capital recovery periods, but should represent a reasonable order-of-magnitude estimate for comparison with the other controls reviewed in this study. Assuming the gas is sold or used at the mine for a price of \$1.70/GJ, the revenue generated would be \$660,000. This reduces the annual cost to \$205/tonne methane reduction.

Taking the capital recovery period as 10 years reduces the total annualized cost to \$1.1 million and the cost-effectiveness to \$150/tonne CH_4 without gas sales, or \$55/tonne CH_4 with gas sales. By comparison the estimate by CH_4 International (P.Comm., 1991; see also Masszi and Proudlock, 1989) of \$20,000/well/yr (over 10 years) leads to an estimate for cost-effectiveness of 20,000/(7000/16), or \$46/tonne of CH_4 emissions reduction.

The range of estimates for cost-effectiveness for open-pit demethanation is then from \$55 to \$150 per tonne of CH_4 emission reduction, over a 10-year period. If coal mining operations shorten the time period allowed for degasification to 3 years, the high end estimate becomes \$200 - \$300 per tonne. Lower costs may be achieved through the use of less expensive technology and operating practices and by accounting for both salvage and the value of water drainage to subsequent mining operations.

d) Other Benefits and Impacts

The CBM gas may be sold or used to displace some other energy supply. A backup energy supply would have to be maintained.

Water disposal costs not considered here may be high in some cases and could affect the feasibility of a particular project. High dissolved solids levels are expected for the produced water in B.C. and disposal becomes a problem if the volumes are high.

Coal mining operations potentially would be disrupted. While no specific schedules could be offered here, simply requiring that coal mining in some instances be put on hold for several years while degasification takes place may hinder development of coal resources.

The only alternative is for the industry to coordinate their coal and CBM recovery operations to minimize the disruption to both.

4. Gas Production Fugitive Emissions

a) Description

Methane emissions from the oil and gas sector originate to a large degree during gas production, with fugitive emissions forming the largest component. While energy demand is predicted to continue to increase in the long-term, proportional increases in fugitive methane emissions are not expected since newer production equipment and piping should leak at much lower rates (IPCC, 1990). Nevertheless improvements can be made to existing facilities in oil and gas production and processing through leak detection and repair (LDAR) programs or the like. The cost-effectiveness of such programs for B.C. would best be determined using data on the number, type, size, age and condition of facilities in place across the Province. Unfortunately such detailed data are not available currently in a readily accessible form, although a pending upgrade to the MEMPR database may provide a starting point for such a study in the near future. However cost-effectiveness and emission reduction data from similar programs for petroleum refineries can give some indications.

Inherent in the use in this study of emission factors from the inventory prepared for the CPA (Picard & Koon, 1990) for gas production facilities is the assumption that fugitive emissions are the largest contributors (55% of total) within this sector, and process venting emissions attributed to gas controllers are the second most significant source (at roughly 35%). The emission factors for these are under review in field validation studies from which results are expected in the next year (CPA Phase II for Alberta, and by the Gas Research Institute for operations in the U.S.A.). As well, the fugitive emissions component of the inventory is determined in part by assumptions on the number, type, condition etc. of facilities in the field which, for the

CPA report and so this study, were developed for the relatively large number of facilities in Alberta compared to British Columbia. This may lead to an overestimate of emissions for this Province. The emissions inventories for VOC and CH_4 should be re-evaluated in light of the results from these studies and others (e.g. Serne, 1991).

For this report, estimates of cost-effectiveness for natural gas production LDAR programs are made based on those developed for process equipment at gas processing plants, refineries and chemical plants, and as such will provide only a guideline. The cost estimate is expected to be low for field equipment because of their remote location.

In a typical gas plant baseline fugitive VOC losses may be apportioned roughly as 58% (of total emissions) from valves, 2% from pressure relief valves, 21% from open-ended lines, 2% from compressor seals (underestimate), 3% from pump seals, 1% each from the inlet gas and liquids sampling connections and 14% from flanges and connections (U.S. EPA, 1983). Recent work for organic chemical plants in Canada attributed overall 58% of fugitive emissions to valves, 11% to pressure relief valves, 2.4% to open-ended lines, 3.9% to compressor seals, 6.4% to pump seals, 1.6% to sample connections and 16.5% to flanges (Edwards and Quan, 1991), which is a very similar breakdown overall to that for gas plants except for the offsetting differences for relief valves and open-ended lines.

A more recent review identified expected control efficiencies for various LDAR programs which are shown in Table IV-1 (from ENSR, 1991). Equipment modifications are specified as part of the more intensive control programs - e.g. dual mechanical seals are required for the control alternatives D and E. Currently available technology for single, tandem and dual mechanical seals will allow for compliance with present and expected regulations in the U.S.A. (Adams, 1991).

TABLE IV-1 EFFECTIVENESS OF VARIOUS CONTROL OPTIONS TO REDUCE FUGITIVE HYDROCARBON EMISSIONS FROM PETROLEUM REFINERY EQUIPMENT LEAKS

	Control Alternatives									
	A		B		C		D		E	
Source	**Inspection Interval**	**Equipment Specification**	**Inspection Interval**	**Equipment Specification**	**Inspection Interval**	**Equipment Specification**	**Inspection Interval**	**Equipment Specification**	**Inspection Interval**	**Equipment Specification**
Valves Gas/Vapour	Quarterly	None	Quarterly	None	Quarterly	None	Monthly	None	None	Sealed Bellows Valve
Light Liquid	Yearly	None	Quarterly	None	Quarterly	None	Monthly	None	None	Sealed Bellows Valve
Open-ended Lines (purge,drain, sample lines)	None	Cap	None	Cap	None	Cap	None	Cap	None	Cap
Sampling Connections	None	None	None	Closed purge sampling	None	Closed purge sampling	None	Closed purge sampling	None	Closed purge sampling
Pump Seals Light Liquid	Yearly[a]	None	Monthly[a]	None	None[a]	Dual Mechanical Seals Controlled Degassing Vents	None	Dual Mechanical Seals[b] Controlled Degassing Vents	None	Dual Mechanical Seals[b] Controlled Degassing Vents
Relief Valves	Quarterly	None	None	Rupture Disks	None	Rupture Disks	None	Rupture Disks	None	Rupture Disks
Compressor Seals	Quarterly[c]	None	None	Controlled Degassing Vents	None	Controlled Degassing Vents	None	Controlled Degassing Vents	None	Controlled Degassing Vents
Expected Ctl Efficiency:	69%		77%		79%		82%		93%	

[a] For pumps,instrument monitoring would be supplemented with weekly visual inspections for liquid leakage. If liquid is noted to be leaking from the pump seal, the pump seal will be repaired.

[b] A pressure sensing device should be installed between the dual mechanical seals and should be monitored to detect seal failure.

[c] Quarterly monitoring and repair is not generally an effective control technique for all compressors. In some instances, compressor repair may necessitate a process unit turnaround because compressors generally are not spared.

SOURCE: ENSR (1991)

A protocol for an effective fugitive emissions control program incorporates:

- Statement of Objectives
- Organizational Structure
- Manpower/Equipment Requirements
- Monitoring
- Data Management Plan
  - Background data, inspections procedures, maintenance plan,and reporting
- Training
- Quality Improvement
  - Maintenance Practices, Equipment Design, and Control Measures
- Costs of Plan Maintenance/Quality Improvement

Significant manpower and equipment resources are required on the part of the operating company in order to assemble an effective program.

b) Capital and Operating Costs, Emission Reduction and Cost-effectiveness

The most reliable costs estimates that may be applied to LDAR programs for production facilities are those cited in the CPPA discussion paper (ENSR, 1991) which are updated here in Table IV-2.

It is expected that costs for LDAR programs for facilities upstream of the processing plant may be higher than those shown in Table IV-2, given additional time requirements for travel to service equipment at a large number of sites in the field. A more accurate indication should be available next year from the Gas Research Institute review and Phase III of the CPA project (for Alberta), which will provide an assessment of the currently available fugitive emission

TABLE IV-2 SUMMARY OF THE INDIVIDUAL COMPONENT CONTROL IMPACTS

Fugitive Emission Source[a]	Control Technique	Emission Reduction (Mg/yr)	Average Cost-effectiveness		Incremental Cost-effectiveness	
			($/t)[b]	($Cdn/t)[c]	($/t)[d]	($Cdn/t)[c]
Pressure relief devices	Quarterly LDAR	4.4	(170)	(280)	(170)	(280)
	Monthly LDAR	5.3	(110)	(180)	250	410
	Rupture disks[e]	9.8	410	680	1000	1650
Compressors	Controlled degassing vents	16.5	150	250	150	250
Open-ended valves	Caps on open ends	2.8	460	760	460	760
Sampling connection systems	Closed purge sampling	2.6	810	1300	810	1300
Valves	Quarterly LDAR	66	(110)	(180)	(110)	(180)
	Monthly LDAR	77	(60)	(99)	310	510
	Sealed bellows valves	110	4700	7700	16700	27500
Pumps	Annual LDAR	3.0	860	1400	860	1400
	Quarterly LDAR	9.8	157	260	(140)	(230)
	Monthly LDAR	11.5	158	260	170	280
	Dual mechanical seal system	13.9	2000	3200	10900	18000

[a] Costs (1980 U.S. Dollars) and emission reductions are based on fugitive emission component counts in Model B from the BID for the proposed standards, EPA-450/3-81-015a, page 6-3, and from Tables A-2 through A-13 of Appendix A. Model includes 14 pump seals; 260 gas service valves and 500 light liquid service calves.

[b] Average Cost-effectiveness = net annualized costs per component/annual VOC emission reduction per component. Savings shown in parentheses.

[c] Costs updated to second quarter 1991 using the Marshall & Swift Equipment Indices and a representative July '91 Cdn-U.S.A. exchange rate, as $Cdn (1991) = $U.S.(1980) x 928.6/659.6 x 1.17.

[d] Incremental Cost-effectiveness = (net annualized costs of the control technique - net annualized costs of the next less restrictive control technique)/(annual emission reduction of control technique-annual emission reduction of the next less restrictive control technique).

[e] Underlined control techniques were selected as basis for standards.

SOURCE: After ENSR(1991)

factors, and of the costs associated with LDAR programs for the upstream oil and gas industry.

c) Other Benefits and Impacts

Benefits include reductions in VOC (as well as methane), emissions and the potential economic advantages for some aspects of the LDAR program. Another potential benefit is the reduced amount of liquid leaks, thus reducing wastewater treatment requirements. On the negative side, the more frequent replacement of existing equipment (e.g. seal packing, rupture disks) will create a small amount of solid waste (U.S. EPA, 1983).

With the results from studies required in the CCMEs NO_x/VOC Management Plan for the petroleum industry to design and implement comprehensive fugitive hydrocarbon emission program for refineries and organic chemical plants, and to refine cost estimates for control of VOC emissions from major sources, and current research underway by the Canadian Petroleum Association and the Gas Research Institute (Lott,1991) on emissions and cost-effective control techniques (both should be completed next year), more refined cost-effectiveness estimates for production facilities in B.C. will soon be possible.

5. Other Types of Control Measures

(a) Economic Incentives and Other Measures

This section provides a brief review of a range of economic and other instruments that are available to bring about a reduction of CH_4 emissions. As will be seen, each of these instruments has relative merits in respect of overall objectives and specific efficiency criteria.

i) Taxes on High Emitters of CH_4

This instrument consists of levying a tax on the emitter in an amount that reflects the estimated damage done. To distinguish these types of taxes from emission fees charged according to the amount of emissions (see below), they are normally considered to be levied on activity measures such as tonnes of industry production, installed thermal capacity, tonnes of solid waste disposed, etc. Variants of such taxes include those that trigger at certain threshold levels of activity or when certain types of production technologies are utilized.

To be optimal, such taxes must be set equal to the marginal damage that occurs at the optimal level of emissions. In turn, to determine the optimal level of emissions, a damage function needs to be estimated showing how damage varies with the level of emissions and the monetary value of this damage. An optimal level of emissions exists when the marginal damage from emissions is equal to the foregone marginal (private) benefits from a reduction in the level of the emission-causing activity.

This type of tax offers the advantage that, compared to standards set without taxes, it tends to be a lower-cost method of achieving a given standard. This is because emitters which have low-cost emissions control options available, will have an incentive to reduce emissions rather than pay the tax. Emitters facing high emissions control costs will tend to prefer to continue at their existing level of activity and pay the tax. Abatement activity is therefore focused on emitters with lower abatement costs, which is economically efficient. As a further consideration, emitters may continue to be taxed even when they scale back their activities to produce the optimal level of emissions, thereby providing a continuing incentive to find new technical means to reduce emissions (which, as described further below, is not the case when only standards are used). Whether this type of tax is a least-cost solution depends on the other mechanisms that are available for achieving a given standard, such as tradeable permits (see below).

The informational needs of this approach are formidable, however. The damage function, in particular, is very difficult to estimate in the case of greenhouse gases because of the need to trace the linkages between the source emissions, changes in the global climate and resulting socioeconomic effects. The difficulty of estimating the damage function explains perhaps why actual examples of such taxes are few and far between.

ii) Rebates on Low Emitters of CH_4

This approach consists in providing rebates or subsidies to emitters whose emission levels fall below certain prescribed levels. The setting of an optimal rebate basically parallels the setting of an optimal tax, in sofar as the various informational requirements are concerned. A rebate approach therefore offers the same types of advantages and involves the same kind of information difficulties as a tax approach. The essential difference is that a tax involves a transfer of revenues into the public sector and a rebate transfers revenues out of the public sector.

A rebate approach involves, however, an additional potential drawback as compared with a tax approach. Given normal assumptions about industry cost curves, the introduction of a tax will cause industry output to fall and hence emissions to fall. However, while the average emissions per emitter will fall under a rebate approach, the industry may expand as a result of the subsidy so that the aggregate level of emissions actually increases. In effect, a rebate system runs the risk of altering the exit and entry conditions into the industry in such a way that, instead of reducing emissions, it may actually increase it.

iii) Emission Fees

Emission fees involve making the emitter pay a sum proportional to the amount of the emissions (e.g, dollars per kilogramme of CH_4 emitted). If the emission fee is calculated on the basis of the marginal damage function, the emitter pays for the exact amount of damages it causes at the margin and in this sense the emission fee is at an optimal level.

Again, however, it is extremely difficult to achieve this optimum because of the problems involved in ascertaining the damage function. This is why the levying of emission fees is usually linked to a pre-existing emission standard. The emission fees then serve as an economic incentive enabling a particular emission standard to be achieved efficiently. The fee is then a function of the emitter's control costs and is fixed at such a level that it brings about a desired level of control.

In principle, emission fees offer the following advantages:

- they oblige the emitter to include in his overall production costs the cost of the controls he is induced to install and/or the cost of the damage caused by residual emissions. In effect, these fees bridge the gap between private and social costs.

- they promote decentralized decision-making, since they enable each emitter to choose the arrangement of measures which will be most effective in his particular situation.

- they provide an incentive to the emitter to adopt the best solution and to constantly improve the control processes so as to reduce costs. In particular, they induce emitters who have access to low-cost control measures to install higher levels of control than emitters whose costs are high, thereby promoting greater efficiency.

- the fees collected provide financial resources which can be made available for mitigating damage and/or financing emission control facilities for joint use.

iv) Emissions Trading

This instrument is based on the principle that, since environmental policy cannot be grounded on equalizing the marginal social cost of emissions with the marginal social cost of controlling these emissions (these functions being very difficult to ascertain), emission standards should be set by regulation. A standard is defined in terms of an acceptable total quantity of emissions per unit of time. The rights to produce emissions within this acceptable total ceiling are then sold by the government, or otherwise allocated, following which the rights can be traded in an open market among emitters.

This method offers the following advantages:

- it avoids the difficulty of calculating the damage function.

- the total cost of emissions control is minimized compared to an approach of setting uniform standards (see discussion of command and control strategies below). This is because emitters with higher costs of control will have a greater preference for buying permits, while emitters with lower costs of control will have a greater preference to sell their permits.

- it opens up the possibility of varying standards with comparative ease. The regulatory authority can intervene to either tighten or relax the level of controls by entering the market, either to purchase existing permits or sell new permits.

- the market can be open to private parties who are affected by the emissions to purchase (and retire) permits so as to lower the overall level of emissions. Being based on a market willingness to pay, such actions promote economic efficiency. A corresponding disadvantage is the possible adverse reaction by government to having private parties alter the level of total emissions that had been determined by the government to be acceptable.

- it avoids some of the problems of taxes described earlier. Even when a standard is set and taxes are used to achieve it, there are risks that the tax will be mis-estimated. With tradeable permits, it is not necessary to identify both the desirable standard and the relevant tax rate; it is necessary to identify only a standard and find a mechanism for issuing permits. Taxes also require adjustment because of entry to, and exit from, the industry, whereas tradeable permits adjust readily to such changes.

Two practical disadvantages of the tradeable permit system should be noted:

- the regulatory authority needs always to know the magnitude of the emissions permits held by each emitter, which can cause problems especially when emissions permits change hands frequently.

- some challenging technical issues have to be tackled in designing the actual type of tradeable permit system implemented (e.g., ambient permit, emissions permit, pollution offset permit). Technical aspects of tradeable emission per mil design are discussed by Tietenberg (1985).

v) Energy Conservation

In formulating CH_4 control instruments, it is important to bear in mind that an increased control of these emissions may produce considerable benefits of other kinds. In particular, increased energy conservation as a means to (jointly) reduce energy use and CH_4 emissions provides benefits in terms of reduced requirements for fossil fuels, reduced energy conversion facilities, reduced health effects from air emissions and reduced environmental conflicts associated with energy supply. In effect, therefore, the energy conservation benefits of CH_4 control measures should be entered as credit against the costs of such measures as they pertain to the control of CH_4.

An obvious advantage of using energy conservation as a means to control CH_4 emissions is that such projects may be attractive in and of themselves, while reducing greenhouse gases as a beneficial side-effect. A potential disadvantage of this approach is that it relies on energy conservation incentives as the driving force in emissions reduction, and the strength of these incentives as between the different emitting sectors (e.g., landfills, natural gas industry, agriculture) may not correlate well with the relative importance of these sectors in total emissions.

vi) Command and Control Regulation Strategies

Direct controls are based on the principle of an absolute obligation to comply with emission standards fixed by regulation. This means that all emitting activities must comply with regulations directly enforceable by means of legal measures and not through the operation of economic instruments. The standards may concern the rates of emission, the average quality of the receptor body or the characteristics of the production process.

A command and control strategy clearly is of definite advantage to the environment, since it determines the objectives and their means of achievement without being dependent on the effects of economic incentives. Direct controls offer the most certain means of preventing irreversible effects or unacceptable pollution and arguments might be made about the extent to which global warming due to CH_4 emissions fits into these categories.

However, a command and control strategy has certain drawbacks:

- it can involve high administrative and compliance costs.

- economic efficiency is reduced, since no economic mechanism operates to enable the standards to be attained at least cost. Differentiated standards suited to the special conditions of each emitter or type of emitter (say, industrial combustion sources, or beef and dairy operations) might be developed to achieve more economically efficient control, but this imposes greater informational needs.

- direct controls do not provide real incentives as such, since emitters may be content to simply comply with the regulations, having no incentive to surpass the standard, such as they might have with emissions trading.

It should be noted that direct controls are often preferred by governments and industry. To government, they are a clear-cut concept that can be integrated readily into the existing administrative and legislative framework. To industry, they open the way to negotiation and compromise over the fixing of differentiated emission standards.

vii) Comments on Alternate Control Instruments

Two main conclusions emerge from this brief review of the pros and cons of alternative instruments for the control of CH_4 emissions. First, there are significant informational requirements for implementing a number of these approaches. Secondly, the analytical requirements for making a rational choice among the alternative instruments are also significant. In particular, since the characteristics of the emitting sectors are so diverse, differences should be expected in the effectiveness of particular across the different sectors. For example, an instrument might be suited to anthropogenic sources but not to natural sources, and an instrument suited to a public sector activity (e.g., landfills) or regulated activity (e.g., natural gas transmission and distribution) might not be suited to a private sector activity (e.g., industrial combustion).

It would be premature to conclude that any one of the alternate approaches (or combination of approaches) at this time is preferable. It certainly appears there would be merit to investigating the different approaches in greater detail and in the context of specific sectors, outside of the more immediate inventory objective of this study.

In the absence of a more detailed study, it appears that the energy conservation approach offers particular promise as a means of controlling these emissions, based on the likelihood that this approach will be very cost competitive when judged on a net cost basis. It is also consistent with the findings of a recent evaluation of projects funded under the federal Industry Energy Research and Development (IERD) program which indicate the efficacy of employing environmental solutions as an inherent part of technical innovation (CANMET, 1991). Evaluation studies of energy conservation projects have found that, in many instances, when a firm or industry has decided to implement an energy efficient process, environmental benefits have, in varying degrees, automatically followed and in some cases have turned a marginal project into a fully viable project.

(b) Controls for Mobile Sources

On-road motor vehicles emitted 6,929 tonnes of methane in B.C. in 1990, 77% of the total from all mobile sources, including on and off-road motor vehicles and aircraft, rail and marine sources. By comparison the total from combustion sources other than incineration (e.g. power generation, industrial, pulp and paper etc.) was only 1,070 tonnes. Incineration of woodwaste, producing 6,699 tonnes of methane, was the only combustion source comparable in magnitude to the mobile source sector.

Combustion sources produce, in addition to other pollutants, carbon monoxide (CO), which competes with methane in reactions with hydroxyl radicals (OH) in the atmosphere and so reducing the atmospheric sink for methane. Limiting emissions of CO and VOCs, which also react with OH, will tend to increase the sink for methane.

Some control or mitigation measures designed to reduce emissions of HC, CO and NO_x from on-road motor vehicles will tend to reduce, as well, emissions of methane. For example, if there are fewer vehicles on the road, because more commuters are car pooling or taking mass transit, then reduced emissions would be expected for each pollutant. Numerous Transportation Control Measures (TCM) have been proposed or implemented in various urban areas in the U.S.A., and these are being reviewed currently for potential application in the GVRD.

Emissions may be reduced through TCMs that reduce the number of vehicle-kilometres-travelled (VKmT), number of trips made, and/or average speed of travel. Reducing VKmT (e.g. through shorter commutes through land use management, or with Park & Ride (lots for the Skytrain) reduces the total amount of emissions from the exhaust and from evaporative HC losses (calculated on the basis of grams per kilometre) but does not reduce cold-start or hot soak emissions (both calculated as gms/trip) which occur at the beginning of the trip and after parking at the end of the trip respectively, and which can comprise half the hydrocarbon emissions on a given trip (Dulla et al., 1991). Diurnal evaporation losses as well would not be affected. TCMs that reduce (VKmT) and number of trips made include incentives to use mass transit or car pooling (e.g. with high occupancy vehicle lanes), biking, or walking. Similarly, measures such as a reduced work week or telecommuting would accomplish reductions in VKmT and number of trips.

Minimising the amount of low speed travel will reduce hydrocarbon and CO emissions substantially because their respective emission rates increase rapidly as vehicle speeds drop. Intersections often may become CO "hotspots" as vehicles slow down, queue and then accelerate through.

Synchronising traffic lights to allow for a freer flow of traffic throughout the day will tend to reduce emissions that occur at intersections. Reducing truck traffic during rush hours (in an effort to reduce traffic congestion as well as reduce the relatively high emissions from the trucks operating at lower speeds), installation of one-way streets, reversible lanes and left-turn bays, and limiting parking on streets that have high traffic volumes would all tend to reduce traffic congestion, increase traffic speed and decrease emissions. It is important that TCMs be implemented that reduce congestion throughout the day (and not just at rush hour) as the daily commute may not be the major contribution to VKmT or number of trips made during the day, but rather only account for a fraction of that (e.g. roughly 20% as in San Francisco; Deakin, 1991).

Emissions may be reduced through the effects of regulations that address technology, such as those regarding high mileage vehicles, alternative fuels programs, and emission control inspection and maintenance programs. Two disadvantages commonly associated with high-mileage vehicles are, firstly, safety concerns, as high-mileage vehicles tend to be lighter, and secondly, their potentially limited effectiveness in reducing emissions. The safety concerns may be alleviated by mandating complementary improvements in safety features, e.g. air bags, anti-lock braking systems, crumple zones, and protection from side-collisions. The effectiveness of high-mileage vehicles may be somewhat reduced if VKmT increases in response to lower operating costs (for fuel).

The use of alternative fuels has been of increasing interest recently due to the potential for improving air quality, lowering emissions of greenhouse gases, and (in the U.S.A.) to reduce dependence on imported oil (Wolff and Frosch, 1991). To compare these fuels on the basis of greenhouse gas emissions requires consideration of emissions involved in the production, processing, distribution and end-use of the fuel as well as emissions related to the acquisition and delivery of fuel feedstock to the production plants, and the relative differences in emissions in the assembly and manufacture of the materials used in vehicle production (Acurex Corp., 1989; Klausmeier and Draves, 1991). The bulk of the greenhouse gas effect may be attributable to vehicle emissions and, to a smaller extent, to fuel production. This effect in one study was calculated considering the global warming potential of each of CO_2, CH_4 and N_2O for each fuel type, with the result that compressed natural gas (CNG) is favoured over both 85% methanol and gasoline for light duty vehicles, and liquified petroleum gas (LPG) favoured over diesel, CNG and methanol for heavy-duty vehicles (Klausmeier and Draves, 1991).

Inspection and maintenance programs can be effective in reducing mobile source emissions. There are high expectations for the one planned for the Lower Mainland (Ashby et al., 1991), because it was designed taking into consideration factors determined from similar programs in the U.S.A. to be key elements for a successful program (e.g. centralised loaded mode testing, certified mechanics, comprehensive underhood inspections etc).

Taxes and other economic measures were discussed in the previous section and therefore are only briefly discussed here. Experience has been (EPA Economic Incentives Task Force, 1991; U.S. Congress Office of Technology Assessment, 1991) that substantially increased fuel costs (i.e. from taxes) are required before a significant effect is observed on motor vehicle usage (VKmT and number of trips made). Inequity is observed as there is a disproportionate effect on low-income householders. Increased gas taxes would be even less effective in B.C. if more motorists respond by buying their gas in Washington.

Convenient, practical and safe alternatives to the use of the private automobile must be available before people can be expected to leave their cars at home more often. This can be encouraged with economic measures such as incentives to switch to alternatively-fuelled vehicles, high mileage vehicles and/or getting vehicles identified as high emitters off the road (e.g. as part of an emissions trading package, or with a sipper rebate/guzzler fee, or equivalent, combination) and commercial zoning practices to affect land use planning to reduce the need to use a private automobile (to commute, shop etc).

The use of existing transport related revenue (taxes on gasoline, registration fees, tolls, etc), e.g. as done in Oakland (Oakland Metropolitan Transportation Comm., 1990), is a more preferable means of funding these mitigation measures than new taxes. It would be a specific application of the more general principle that the (Sanghi et al., 1991) "impact of a carbon tax on carbon emission mitigation would be minimal unless the revenues from the tax are dedicated to finance carbon reduction measures". For example, vehicle taxes and rebates can be combined in a revenue-neutral program in which revenue from taxes is redistributed through rebates (U.S. Congress Office of Technology Assessment, 1991). e.g. consumer rebates on the purchase price may be offered for a limited production run of the winning vehicle(s) of a competition among vehicle manufacturers to produce high mileage/alternative fuel/electric vehicles.

6. Summary of Cost-Effectiveness Determinations

The foregoing case studies yielded nominal values for the cost-effectiveness of candidate control measures for the larger methane source sectors. For ease of reference, these have been summarized in Table IV-3. The only control measure which could potentially yield a cost saving is leak detection and repair for valves at an oil/gas processing plant. This would only apply to a large central facility comparable to an oil refining complex, for which the cost was originally estimated. The degasification of coal seams is

TABLE IV-3 SUMMARY OF COST-EFFECTIVENESS DETERMINATION

Control Measures	Cost Effectiveness ($/tonne CH_4 reduction
Landfill Gas Recovery	
without gas sales	280
with gas sales	200
Manure Treatment	
Anaerobic digestor with engine/generator set	1000
Aerobic digestor	500
Degasification of Coal Mines	
10 yr amortization - without gas sales	150
- with gas sales	55
3 yr amortization - without gas sales	300
- with gas sales	205
Fugitive Emission Leak detection and repair programs for processing plants (based on data for refineries)	(99)[a] (for valves) 260 (for flanges) 680 (for pressure release valves)

[a] Cost savings shown in parentheses.

technically difficult and very site-specific, which may not be totally reflected in the calculated cost-effectiveness.

V. ANALYSIS OF MANAGEMENT STRATEGIES

A. EVALUATION CRITERIA

Evaluation criteria that would be expected to be integral to the final design of public policy on greenhouse gas emission are efficiency, equity, administrative simplicity, transparency, and improved environmental quality (Lave and Gruenspecht, 1991). These are discussed briefly here so that the overall assessments can be made both on the basis of the results from the case studies presented for the preferred measures, and qualitatively in the context of some of these broader criteria. As well, the required control actions are presented in a global context.

The first of these criteria, efficiency, refers to the cost-effectiveness of control measures, both in the sense of cost relative to the amount of environmental gain achieved (e.g. that following the emissions reduction) and in the sense of selecting the most appropriate or favoured action to take e.g. to control CO_2, CH_4, both or neither. For example, a carbon or fossil fuel tax implemented in some (e.g. industrialised) countries would be expected to reduce the demand for those fuels within those countries; however outside the participating countries, prices would be expected to drop due to overall decreased demand. This would lead other countries (e.g. poorer, developing countries) to increase their use of those fuels, thereby offsetting or negating any intended emission reduction. Thus, carbon taxes implemented within only a few countries may not be "efficient" when viewed in a global context.

The question of equity refers to the ethical and political ramifications of the controls, usually in the sense of ensuring that unreasonable costs are not being imposed on certain groups in the name of benefits for other groups e.g. fuel taxes may take up or represent a disproportionately larger share of income to low-income households relative to those more affluent (U.S. Congress Office of Technology Assessment, 1991). Another example would be jobs that may be lost in some industries due to the costs of environmental controls such as was the case (Lave and Gruenspecht, 1991) when the U.S. Congress required the installation of scrubbers on coal-fired power plants rather than a switch to low sulphur coal, thus preserving coal mining jobs in the U.S.

Administrative simplicity refers to the (administrative) efforts required to implement the control measures. For example, setting up monitoring and reporting requirements for every landfill in the Province may not be feasible. Similarly, the administrative requirements for various types of economic incentive programs may differ significantly, with accompanying differences in costs.

Transparency of a program refers to how likely that program, as perceived by the public, is to achieve its stated goals. Examples of programs that may be perceived poorly are taxes on fuels and emission fees, which may be seen as revenue-generation devices rather than ones aimed at emission reduction. A less obvious example relates to the implementation of an emission permitting program; first the government must decide on an allocation of permits, which by definition have economic value, to various industries and must do this in a way that is perceived as fair and leading to a net environmental benefit. This may not be an easy task to accomplish to the satisfaction of the public or the media.

The final criterion of improvement in environmental quality requires that control actions that meet the above four criteria should as well actually lead to a significant net improvement in the environment. In the context of this study, it is necessary to have substantial emission reductions from the largest sources of methane in the Province, in order to realise a net environmental benefit regarding global warming.

In a global context, the required control actions or management strategies considered here for the Province in part are those that relate directly to emissions of methane within B.C. and in part to those policies that affect emissions in other countries. While this report specifically addressed only methane emissions within B.C., it is helpful to view these in a global context.

A 10 to 15% global decrease in anthropogenic methane emissions is required in order to stabilize atmospheric methane concentrations at their current levels (IPCC, 1990). Emissions from ruminants and animal wastes, rice paddies, oil and gas systems, biomass burning, wetlands, coal mining, oceans and freshwater and hydrates (Table V-1) were all estimated as larger or potentially larger sources than landfills in the global budget (IPCC, 1990). However, for the Province, landfills were identified

TABLE V-1 SOURCES OF METHANE EMISSIONS
Megatonnes per Year

	Annual Emissions	Range	Comments
Animals	80	65 - 100	Livestock in developed and developing countries.
Animal Wastes	35	NR[a]	Anaerobic decomposition of organic wastes.
Wastewater	NR	20 - 25	Anaerobic decomposition of organic matter in the wastewater stream.
Rice Paddies	110	60 - 170	Principally in developing countries.
Coal Mining	NR	30 - 50	Surface and (mostly) sub-surface mining.
Oil/Gas Systems	45	25 - 50	Production, transmission and distribution.
Landfills	NR	25 - 40	Decay of organic wastes.
Biomass Burning	55	50 - 100	Forest clearing and waste burning.
Natural Wetlands	115	100 - 200	Tundra, bogs, swamps, alluvial formations.
Termites	40	10 - 100	Bacterial within termites produce CH_4 as part of the termite's digestive process.
Oceans and Freshwaters	15	6 - 45	
Hydrates	5?	0 - 100	Potentially important future source.
Total Emissions[b]	540	440 - 640	Well constrained.

[a] NR = not reported at the IPCC workshop

[b] Total annual emissions of 540 Tg per year ± 100 Tg is well constrained based on observational data. The point estimates of the individual source estimates presented here do not sum to 540 Tg.

SOURCE: IPCC (1990)

as the largest source (anthropogenic or natural) by a wide margin. Landfill emissions in B.C. may become subject to new controls, but effective control of methane emissions globally will still depend on international efforts and thus may provide markets for local technology e.g. degasification of coal mines, fugitive emissions control technology (petroleum industry), landfill gas recovery, ruminants feed management, etc.

Global emissions of greenhouse gases can be affected through programs such as (U.S. Congress Office of Technology Assessment, 1991): technology transfer and trade (e.g. exports of energy - efficient equipment, or fugitive emissions control, CBM degasification and renewable energy technologies); redirecting energy and natural resource policies (e.g. as in loans to developing countries) away from large scale projects such as oil or coal fired powerplants towards energy efficiency programs (e.g. demand side management, policies for higher energy efficiency for motors, etc.) and renewable energy technologies; limiting biomass burning (e.g. forest clearing in the tropics); and building local institutions in developing countries to administer these programs.

Development of methane emission control strategies for B.C. requires consideration of the diverse, site-specific and geographically dispersed nature of the major sources within the Province. To some extent, studies or programs are already underway which may either provide data for more detailed analyses or themselves substantially reduce methane emissions e.g. the 50% reduction in MSW planned for the year 2000 (reducing emissions attributed to landfills), the fugitive emissions control programs outlined in the NO_x/VOC management plan for petroleum and chemical process facilities, energy conservation measures such the demand-side management programs practised by B.C. Hydro and B.C. Gas and supported by the provincial government, and the GVRD Air Management Plan which addresses a range of air quality issues (e.g. mobile source emissions) within the Lower Mainland.

B. EVALUATION OF CASE STUDY CONTROL MEASURES

1. Landfill Gas Recovery

Proven landfill gas recovery technology is available to collect gas from a landfill and either flare it or use it for electrical generation or other energy recovery scheme. Not only will this reduce emissions of methane but also those of carbon dioxide if the energy recovered from the landfill displaces other carbon fuel use. Emissions of odorous compounds, non-methane organic compounds (NMOCs) and air toxics (reducing ozone and health related impacts) will also be reduced. A reduction in the fire or explosion hazard (from methane accumulation) around or near landfills is another benefit.

A definite environmental gain is realised through the use of landfill gas recovery systems, satisfying one of the key criteria. Transparency and equity (other criteria) are also attained, at least for the typical case. Cost-effectiveness and administrative burdens will depend on the particular programs designed and are discussed below.

Administrative costs can be high for the government agency charged with developing, implementing and enforcing landfill gas recovery systems across the Province, especially if most if not all landfills are required to install systems. This cost was not considered in the determination of cost-effectiveness for the case-study presented earlier. It can be reduced following the approach of the EPA's proposed guideline (EPA CFR, 1991) in which landfills which emit less than a prescribed level of NMOCs (150 tonnes/yr) are exempt from having to install gas recovery systems.

For a 150 tonnes/yr NMOC emission rate cut-off, it is expected that many landfills in California under 8 million tons (7.2 million tonnes) will be exempt (CARB, 1990), although that determination is dependent on the NMOC emission rate assumed. In this case study the small (initially 450,000 tonnes) landfill was estimated to emit between one and two hundred tonnes/yr of NMOCs over its ten year lifetime, based on the EPA computer model "Landfill". For the purpose of establishing for regulatory purposes the emission level of a particular landfill for the Province, a protocol should be developed in which representative default values for the "Landfill" model are specified so that a consistent means of estimating NMOC (and methane) emissions is used. The Province would then have a systematic means for determining which landfills would require monitoring and/or gas recovery systems. In the EPA protocol, landfills less than 100,000 tonnes in design capacity are exempt from having to report an estimated NMOC emission rate, thus saving on administrative costs for the small landfills.

Cost-effectiveness will be different for each site in which gas recovery systems are installed, reflecting differences in gas emission rates, system design (which affects capital and operating costs as well as the emission reduction - ranging from 40% to 90% - achieved); potential revenue from gas sales and valuation of other benefits (reduced odours, and NMOC and toxic emissions and fire/explosion hazards, etc.).

For existing and active landfills, the EPA (EPA CFR, 1991) determined gas recovery system cost-effectiveness to be $927, $555 and $407 (U.S. per tonne NMOC) for landfills emitting not more than 25, 150 and 250 tonnes of NMOCs per annum, respectively. For those estimates, most landfills having a design capacity of under 1 million tonnes were in the low-emitting category (under 25 tonnes of NMOCs). Emission reductions assumed for NMOCs for each category ranged from 71 to 92% (50% was used for this study). The cost-effectiveness estimates determined in this study and for CARB (1990) are more than double these, but are believed to be more representative for the Province, as they incorporate more conservative assumptions regarding emission reduction potential and system costs.

The design of a protocol or guideline for landfill gas recovery systems for the Province would have to consider (IPCC, 1990) not only how to define best technologies for gas collection and utilisation for new vs old and active vs inactive landfills but, as well, determine how these will be affected by new waste management practices (e.g. recycling programs, changing MSW composition).

2. Oil & Gas Industry - Gas Production Fugitive Emissions

Emission rates attributed to the oil and gas industry for countries such as the USSR are much higher than they are within the Province, indicating that markets may exist abroad for Canadian technology which if accessed may have more effect on global warming than measures applied locally.

The development of policies designed to reduce emissions associated with operations within B.C. needs more detailed analysis and access to specific details of facilities. Results from the Canadian Petroleum Association on-going studies and the Gas Research Institute review will be useful in this regard.

Cost-effectiveness estimates presented here for hydrocarbon emission reductions show how some aspects of LDAR programs potentially may pay for themselves, e.g. quarterly or monthly LDAR for pressure relief devices and valves, while other ones are costly - e.g. installing dual mechanical seals (on pumps) and sealed bellow valves. The choices primarily are to either implement LDAR programs, or install leak-tight or low-leak equipment for new or modified facilities.

LDAR programs have the advantage that they encourage operators to upgrade their systems (i.e. replace old or worn components which often leak at high rates) and may encourage the phase-out of equipment prone to leaks. The first step is to identify the most important sources to monitor and control. An indirect benefit of LDAR programs is that technology or operating practices developed as part of fugitive emissions reduction program can be sold or licensed to others, particularly in ares with worse emissions, and used as a new source of revenue.

If costs incurred by operators for fugitive emissions reduction programs are passed on to consumers through higher prices then the demand for the products and emissions associated with their production may decline. This is preferable to implementing a carbon tax directly.

Considering the other evaluation criteria, administrative requirements may be significant, but the Province has staff who are familiar with the industry, and the NO_x/VOC plan calls for similar fugitive emission reduction efforts at refineries and chemical plants. Equity should not be a question, at least for the aspects of LDAR programs that are economic, as long as no unreasonable (control) demands are made upon the industry. The program would be transparent and, since fugitive emissions are the greatest source of methane in this sector, a net environmental benefit would be expected.

Other potentially major emission sources within the oil and gas industry are venting losses from well sites (e.g. casing gas) and gas-operated equipment such as controllers. Not enough information is available to analyze control of these sources in B.C. Typically, venting of gas at the wellhead is not documented. Detailed lists of equipment (e.g. number, size, age) at various process units in the field in B.C. are not maintained. It is expected that venting of gas at well sites is a major source of emissions, though a detailed analysis is needed. Gas-operated controllers, which are now a significant source, may be replaced by electronic units, despite the added expense, as the newer types enable remote control and allow the operating company additional flexibility.

3. Degasification of Coal Mines

Costs for degasification of any particular surface coal seams in B.C. may differ significantly from the estimate given here, because of the sensitivity of cost to site-specific characteristics such as the depth, thickness and methane content of the coal seam; location (relative to service industry); and amount and type of wells and surface equipment.

Most emissions globally are from five countries (the United States, the People's Republic of China, the Soviet Union, Poland and South Africa) and it is believed that emissions from these countries will increase substantially in the next 20 years as increasing amounts of coal are mined from deeper and gassier seams (IPCC, 1990). China is attributed approximately one-third of the total, and thus represents a sizable market for degasification technology.

It was not determined in this report that degasification can be applied economically at any particular site in the Province. There may be deeper coal seams that show good potential for CBM recovery, e.g. in southeast B.C. (Johnson and Smith, 1991), but as these are not currently being exploited for coal resources they were not considered for this report. At some point in the future however, they may be mined and degasification prior to mining should be considered then. CBM recovery from deep coal seams is receiving increasing attention in the petroleum literature because of the potential resources and the relatively long life of projects (20 years or more).

The overall assessment is that degasification for surface mining operations was not determined to be cost-effective at this time within the province. Depending on the quality and quantity of gas available, particular sites may become more attractive in the future especially if gas prices rise and deeper (higher gas content) coal seams are involved.

Equity may be a concern if degasification is to be applied to surface mines as it is not clear that methane emissions from these operations are known well enough to warrant control efforts. Administrative efforts would not be a concern since staff for the Province are already familiar with the industry, although some additional staff may be required. The transparency of degasification requirements appear obvious. Whether a significant environmental benefit would be realised is doubtful, unless technology such as available here is applied to larger mining operations such as in China.

4. Manure Treatment - Aerobic Digestion

The cost-effectiveness determined in this study for aerobic digestion systems was determined to be poor. Anaerobic systems appear to be less cost-effective and have tended to be nonviable for typical farming operations (e.g. 200 cow dairy farm) because of operating and maintenance requirements.

Any particular farming operation may have significantly higher or lower emissions than that assumed for the case study, therefore requiring aerobic or anaerobic treatment systems in all cases raises questions concerning environmental benefit and equity. Administrative costs for the Province could be expected to be significant for such a program because of the large number of small operations. Transparency would not be expected to be an issue.

5. Other Measures

Other measures such as economic incentives or disincentives, policy instruments, energy conservation, and stationary and mobile source (combustion) emission control measures discussed in the literature primarily for carbon dioxide will tend as well to reduce emissions of methane. From these, some useful generalizations can be made.

Combustion sources generally produce a small amount of methane (even if it is not present in the fuel) along with carbon monoxide, which tends to compete with methane for the atmospheric sink (hydroxyl radicals). Control measures designed to reduce emissions from combustion sources tend to reduce energy demand (and the associated methane emissions that occur during oil and gas production, processing, transmission and distribution, and from coal mining activities) and increase the atmospheric sink for methane (since less CO would be produced). Energy conservation measures would generally have these effects.

Policy instruments may be considered to include (US Congress OTA, 1991):

- taxes;
- financial incentives;
- marketable permits;
- regulations;
- research, development and demonstration;
- information and public education.

Effective use of these instruments requires careful consideration be given to their effect in combination. For example, a combination of taxes and rebates may be more effective than either alone. In designing these strategies relevant factors to consider are (US Congress OTA, 1991):

- Low cost options are preferred by decision makers in industry and the government but low first cost options are commonly favoured by individuals.

  e.g. Buildings may be constructed in a manner minimizing construction costs (to the owner) to the detriment of its energy efficiency and therefore its energy costs.

- High efficiency technologies tend to have high first costs but lower costs over their life-cycles.

Table V-2 shows policy instruments developed by the EPA office of Technology Assessment (US Congress OTA, 1991) for carbon dioxide emissions that are applicable as methane control measures as well.

C. CONTROL STRATEGIES AND THEIR IMPACT

Many potential control measures were identified for reduction of methane emissions in B.C., as identified and rated in Appendix VII. Because of the large number of possibilities, only a limited number were selected in this study for more detailed analysis. These case studies focus on control measures for major sources, these being of primary importance when considering development of a strategy for reduction of methane emissions in the Province. The case studies consider control measures which have the highest likelihood of being economically attractive.

The control measures were rated using obvious factors which indicate technical and economic viability: technical emission reduction potential; cost; case of implementation; status of development; and time frame. A simple qualitative rating was used for each assessment factor, using experienced judgement.

The technical emission reduction potential was rated as low, moderate or high, based on the extent of reduction which could be achieved for the particular source category. This assessment did not consider the relative contribution of the source

TABLE V-2 POLICY INSTRUMENTS TO REDUCE CO_2 AND CH_4

	TAXES			FINANCIAL INCENTIVES			MARKETABLE PERMITS	REGULATIONS		RD & D		INFORMATION	
	Energy Tax	Carbon Tax	Purchase Tax	Tax Incentive	Low Cost Loans	Direct Payments		Performance Standards	Building Codes	R & D	Demonstration	Labels/ Rating	Audits
Commercial buildings													
Thermal intugrity	✓	✓	-	✓	✓	✓	-	-	✓	✓	✓	✓	✓
Appliance/lighting	✓	✓	✓	✓	-	✓	-	✓	-	✓	-	✓	✓
Usage patterns	✓	✓	-	-	-	-	-	-	-	-	-	-	✓
Residential buildings													
Thermal integrity	✓	✓	-	✓	✓	✓	-	-	✓	✓	✓	✓	✓
Appliance/lighting	✓	✓	✓	✓	✓	✓	-	✓	-	-	-	✓	✓
Usage patterns	✓	✓	-	-	-	-	-	-	-	-	-	-	✓
Transportation													
Small car/truck efficiency	✓	✓	✓	✓	✓	✓	-	✓	-	✓	✓	✓	-
Alternate fuels	-	✓	-	✓	✓	✓	-	-	-	✓	✓	-	-
Off highway[a]	✓	✓	-	-	-	-	-	✓	✓	-	-	-	-
Vehicle km travelled	✓	✓	-	-	-	-	-	-	-	-	-	-	-
Manufacturing													
Efficiency	✓	✓	-	-	-	-	-	-	✓	✓	-	-	-
Recycling	✓	✓	-	✓	-	✓	✓	-	-	-	-	-	✓
Energy supply													
High to low carbon fuels	-	✓	-	-	-	-	✓	-	-	✓	✓	-	-
Renewable	✓	✓	-	✓	-	✓	✓	-	✓	✓	-	-	-
Cogeneration	✓	✓	-	✓	-	-	✓	-	-	-	-	-	-
Efficiency, existing plants	✓	✓	-	-	-	-	✓	-	-	-	-	-	✓
Forests													
Recycling	-	-	-	✓	-	✓	-	✓	-	-	-	✓	-
Increased productivity	-	✓	-	✓	-	✓	-	-	-	✓	-	-	-
Food													
Farm inputs	-	✓	-	-	-	✓	-	✓	-	-	✓	✓	✓
Farm operation & efficiency	-	✓	-	✓	-	✓	-	✓	-	✓	-	-	-
Food processing	-	✓	-	-	-	-	-	-	✓	-	✓	-	✓

[a] Heavy equipment, aircraft.

SOURCE: EPA Office of Technology Assessment, 1991.

category to the total inventory. Generally, those control measures with high reduction potential are more likely to be commercially economic, other factors being the same.

The qualitative assessment of cost was developed without the benefit of detailed cost analysis, making it subject to error, but nonetheless, a useful tool for screening of available options. Cost categories (low, medium and high) were assigned, with obvious limitations, using an arbitrary scale which reflects the likely capital and operating costs within each category. High or medium cost categories are indicative of likely uneconomic control measures. For a given application, quantification of the economic viability of a control measure would need to be determined using site-specific data.

The ease of implementation was rated from low, medium to high based on the perceived technical, logistical or administrative difficulty associated with the control measure. Those having a high rating, can be considered to face high barriers to implementation.

The status of the control measure was rated according to its state of development, which ranges from unknown to emerging to proven. Ranges of status were used when the rating for a particular measure was uncertain. Unknown or emerging status would pose a barrier to implementation and impact on the cost of the control measure.

The final rating criteria was time frame, which was categorized as short (< 3 yrs); medium (4-10 yrs); and long (> 10 yrs) based on expectations. This is purely subjective and will vary for particular control measures depending on many diverse considerations.

It is clear from the case studies, that no control measures for major sources, with the possible exception of those involving energy conservation, are economic in their own right. The cost of control is reduced in cases of significant methane recovery by the revenue generated by methane sales. The cost-effectiveness of control could be deemed to be acceptable if some value was chosen as the division between economic and uneconomic. At this time, no socioeconomic assessments of the impacts of control measures are available which would allow the setting of an "acceptable" cost-effectiveness. Such a criteria would be useful in identifying those measures which could be implemented without significant social or economic costs.

A number of technical control measures were selected from the master list as reasonable for implementation in the short (< 3 yrs) and long-term (> 10 yrs). These were chosen after review of all options for each of the inventory categories. Attention was given to the control measures that were thought to have acceptable economic and social impacts, though this is purely subjective. The measures selected are best considered as illustrative of the levels of control likely possible. More detailed study would be needed to yield a confident estimate of methane reduction and cost-effectiveness, as well as of the socioeconomic impacts.

Table V-3 summarizes the control measures which were selected as a possible control strategy. The assumptions are summarized for each case. Only technical control options were included in the analysis.

The short-term and long-term reduction in methane emissions achieved by the selected control measures is presented in Table V-4. A 13% reduction relative to 1990 could be achieved in the short-term. The reduction achieved increases to 27% relative to emissions in 2005, in the long-term. The long-term control measures yield a net emission of 412 kg, 23% lower than the 533 kt emitted in 1990 from anthropogenic sources. The net emission in 2005 after control are 11% less than the net emissions after short-term control.

TABLE V-3: BASES FOR DETERMINING THE METHANE EMISSION REDUCTION POTENTIAL IN BRITISH COLUMBIA

Source Category	Control Measures and Estimating Assumptions	
	Short-Term (within three years)	Long-Term (after ten years)
1. Combustion		
a) Industrial and Utility	• Boiler Tuning and Energy Conservation • Policy on boiler tuning to apply effectively to 80% of boilers in the Province. Emission reduction potential roughly 10%.	• As in short-term.
b) Incineration		
- woodwaste	• Gradual replacement of beehive burners with silo burners or energy systems. Port Mellon (85 MW) and Williams Lake (55 MW) power plants can consume, at an 85% capacity, 15 PJ out of the 87 PJ of woodwaste presently incinerated in the Province. This is taken conservatively as a 15% reduction in emissions in the short-term.	• As in short-term, but higher percentage of sources affected by rule (from 15% by 1993 to 50% by 2005).
- mobile sources	• Emission Inspection and Maintenance Program (I/M) for Road Motor Vehicles in the Lower Mainland. Emissions are reduced by 20% for 40% of vehicles in the province (on road light duty vehicles in the Lower Mainland).	• As in short-term.
2. Oil and Gas Industry		
a) Oil Production	• No change	• Fugitive emissions represent 20% of total; process vents (gas operated controllers mainly) another 20%. • LDAR to reduce fugitive emissions 50% (overall by 10%). • No change expected for emission from controllers since oil production within the Province is relatively low and is expected to drop significantly by 2005. (i.e. gas-operated controllers are not replaced by electronic or air).
b) Oil Transport	• No change	• Fugitive losses comprising 40% of total for tank farms, pipeline terminals and pump stations are reduced 50% by LDAR programs (overall reduction of 20%).
c) Gas Production	• No change	• Fugitive losses account for 55% of total from this sector, with process vents contributing 40%. • Fugitive losses to be reduced by 50% by LDAR programs • Emissions from controllers to decrease as they are replaced with electronic. A 10% is assumed. • Overall emissions reduced to 30%.
d) Gas Processing	• Quarterly LDAR for valves. Fugitive emissions from valves in gas plants comprise 60% of total emission and are reduced by 70%, for an overall reduction of 40%.	• LDAR achieves 50% emission control.
e) Gas Transmission	• No change.	• Fugitive losses are 30% of total, with pipeline and compressor losses totalling closer to 70%. LDAR reduces fugitive losses by 50% (overall by 15%). Reductions possible for pipeline compressor losses through use of portable gas compressors are not accounted for here, but would be assumed to occur for specific situations where cost-effective.

TABLE V-3: **BASES FOR DETERMINING THE METHANE EMISSION REDUCTION POTENTIAL IN BRITISH COLUMBIA**
Continued

Source Category	Control Measures and Estimating Assumptions	
	Short-Term (within three years)	Long-Term (after ten years)
f) Gas Distribution	• No change.	• Same reduction as for transmission through LDAR (and replacement of older lines).
3. Landfills - MSW	• Landfill gas recovery systems assumed for all sites over 400,000 tonnes of MSW in place. Control efficiency is 50%.	• As in short-term, assume control efficiency to increase to 75%.
- Woodwaste and Pulp waste	• No change.	• Waste disposal reduction increases linearly from 1990 to equal 50% by the year 2000 and remains constant thereafter. • Wood and pulp waste redirected from the landfills by the source-reduction program is combusted in a boiler for which methane emissions are comparatively negligible. • Emission reductions for wood and pulp waste landfills as determined using the EPA model "landfill" are 15% and 20%, respectively.
4. Coal Mines	• Not expected to be feasible technically or economically. • No action assumed.	• No action (N.B. only surface coal seams assumed to be mined in this time to any significant degree, therefore gas recovery programs, not expected).
5. Prescribed Fires	• No action in addition to existing plans to reducing burning by 30% by the year 2005.	• No action.
6. Domestic Animals	• No action.	• Feed management programs to reduce emissions by 10% for 20% of the emissions.
7. Manure	• No action.	• Dairy cattle operations using aerobic or anaerobic digestion systems to reduce emissions by 70%. • 40% rule-effectiveness assumed.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Annual methane emissions from anthropogenic sources for 1990 and 2005 were determined to occur from the following subsectors:

	CH_4 Emissions (tonnes)*	
	1990	2005
Landfills	290,500	282,900
Oil and Natural Gas Industry	60,800	83,600
Manure	58,300	72,600
Coal Mines	51,600	50,800
Domestic Animals	36,600	42,400
Prescribed Fires	17,700	12,400
Mobile Combustion Sources	9,000	7,400
Incineration	6,800	6,800
Stationary Combustion	1,000	1,200
TOTAL	532,400	560,200

* Rounded to nearest 100 tonnes. The sum may not add to the rounded total shown.

Landfills are the main anthropogenic source by a substantial margin, contributing 51-55% over the next 15 years. Eighty seven percent of the anthropogenic emission result from landfills, oil and gas production and distribution, manure and coal mined.

Anthropogenic sources contribute 78% of the emissions from anthropogenic and natural sources.

2. Natural methane emissions total 153,800 tonnes from the following source categories:

	CH$_4$ Emissions (tonnes)*	
	1990	2005
Wetlands	129,900	129,900
Wildfires	17,700	25,300
Wildlife	6,100	7,000
Lakes and Rivers	0	0
TOTAL	153,700	162,300

* Rounded to nearest 100 tonnes. The sum may not add to the rounded total shown.

Any changes in natural emissions are difficult to predict because of the lack of data suitable for forecasting. The estimate for 2005 differs from that for 1990 primarily because of the use of ten-year average for the area burnt by wildfires, which is larger than the area burnt in 1990.

Natural methane emissions from the inventoried sources in 1990 are 22% of the emissions from both natural and anthropogenic sources.

3. Methane emissions from landfills arise from disposal of municipal solid waste, woodwaste and sludge from pulp mills, with contributions of 79%, 17% and 4%, respectively in 1990. A 3% reduction in emissions is forecast to occur by 2005 because of expected reduction in the quantities of municipal waste landfilled in future. The emission estimates for woodwaste and pulp mill wastes is very approximate because of lack of data and uncertainties in the emission estimation model.

4. Dairy cattle are the primary source of emissions associated with anaerobic decomposition of manure, contributing 76% of the amount for this subsector.

5. Methane emissions occur from production, processing, transmission and distribution of natural gas. These sources emitted 43,600 tonnes in 1990, and are projected to emit 76,500 tonnes in 2005 because of growth in natural gas volumes. The majority of emissions (72%) occur from production activities.

6. Beef cattle are the main source of methane emissions from domestic animals, contributing 23,400 tonnes in 1990 and 25,700 tonnes in 2005.

7. Emissions from prescribed fires, oil production and distribution, mobile sources, incineration and stationary combustion sources are collectively small, contributing 51,900 tonnes in 1990 and 34,900 tonnes in 2005, which amounts to less than 10% of the total anthropogenic emissions for these years.

8. The annual uptake of methane in aerobic soils is estimated approximately to amount to 41,000 tonnes. The possible error in this estimate could be high because of the uncertainty in the understanding of the process and the base information.

9. The annual atmospheric uptake of methane by oxidation is estimated to be about 440,000 tonnes, with a range of 350,000 to 550,000 tonnes. Transport of methane to the stratosphere may represent less than 20% of the atmospheric oxidation sink.

10. The composite uncertainty in total anthropogenic methane emissions was estimated to be 19% using a simplistic analysis of precision error. This error suggests 532,000 ± 100,000 tonnes for the anthropogenic emissions. The error in the natural emissions could not be estimated meaningfully because of lack of information about the error in the base data. The uncertainty in the natural emissions is expected to be higher than that for the anthropogenic sources.

11. The greatest uncertainty in the estimates of methane emission exist for the natural gas industry, the oil industry and industrial landfills (woodwaste and pulp mill wastes). The following data gaps limit the accuracy of present estimates:

Industrial landfills
- waste quantities in place
- emission rates

Natural gas industry sources
- fugitive emission factors
- detailed inventories of equipment subject to fugitive leaks

Oil industry sources
- fugitive emission factors
- detailed inventories of equipment subject to fugitive leaks

12. Uncertainty exists in the estimate of emissions from municipal landfills as a result of lack of data on the rate constant, gas generation potential, the quantity of waste in place and the recovery efficiency of existing gas recovery systems. Improved data in these areas would allow better estimates to be made using the U.S. EPA landfill model.

13. The estimated cost of effectiveness of methane control measures for major sources calculated as the equivalent annual cost divided by the tonnes of methane emission reduction, were found to be:

Control Measures		Cost Effectiveness ($/tonne CH_4 reduction
Landfill Gas Recovery		
without gas sales		280
with gas sales		200
Manure Treatment		
Anaerobic digestor with engine/generator set		1000
Aerobic digestor		500
Degasification of Coal Mines		
10 yr amortization	- without gas sales	150
	- with gas sales	55
3 yr amortization	- without gas sales	300
	- with gas sales	205
Fugitive Emission Leak		
detection and repair programs		
for processing plants		(99)[a] (for valves)
(based on data for refineries)		260 (for flanges)
		680 (for pressure release valves)

[a] Cost savings shown in parentheses.

14. Landfill gas recovery systems are attractive for the following reasons:

- methane emissions may be reduced by up to 90% with suitable design features;
- the recovered energy may be used to displace other energy supplies;
- emission of odorous gases is reduced;
- problems with off-site migration of landfill gas are eliminated.

A significant potential exists for greater application of landfill gas recovery in the Province. In addition to landfill gas recovery systems, actions are needed to reduce the quantities of wastes landfilled. The analysis in this study considered a system for a landfill with 450,000 tonnes in place in the first year of operation, increasing by 50,000 tonnes/year.

The economic viability of a landfill gas recovery system depends to a considerable extent on the gas price received and the gas cleanup required. At the gas price which could likely be attained in B.C., (presently on the order of $1.40 - 1.60/GJ), a landfill gas recovery system is not expected to be economically viable without some form of subsidy.

15. Methane emissions may be reduced by anaerobic or aerobic processes, with the latter being more technically viable for on-farm application because they are simpler and less costly to operate and maintain. Aerobic systems are also the lower cost option. Aerobic treatment leads to a 70% methane emission reduction for a dairy farm application. Although no valuable products are generated by such systems, there would be a reduction in odours and water quality impacts.

16. Degasification of coal mines to reduce methane emissions appears potentially attractive because of the large quantities of methane involved and the proximity of the energy load of the mine operations. However, the mines in British Columbia are not well suited to the application of this technology. The technology for coal degasification for B.C. mines is not proven and a detailed study would be needed to ascertain the technical and economic viability of such a control measure with confidence. The main obstacles to successful use of this control measure are the shallowness and complex geology of the coal deposits, as well as the logistics of degasification of the coal prior to mining. Development of coal degasification technology in B.C. for application elsewhere in the world in coal deposits having high emissions and more suitable characteristics is worth consideration.

17. Methane emissions from natural gas production, processing and distribution could be reduced by actions which reduce fugitive losses, the most common being implementation of leak detection and repair (LDAR) programs. Studies completed to date on the uses of LDAR pertain to petroleum refineries and organic chemical plants, so data on the effectiveness of LDAR for natural gas

facilities are unknown. The cost of LDAR can be expected to be much higher when applied to remote facilities compared to a large centralized facility. There is a potential in some facilities for LDAR to be economic or, at least, to have a relatively attractive cost-effectiveness.

LDAR programs are included in the NO_x/VOC management plan for refineries and organic chemical plants. Development of a code of practice for fugitive emissions from these facilities has recently been initiated and will include large gas plants, leading to some progress in the identification of operating and maintenance practices as well as performance standards which will reduce methane emissions. Studies are presently underway to improve the understanding of fugitive emissions from the natural gas sector.

It is clear that more work is necessary to determine the specific control measures for subsectors in the natural gas sector. A detailed study of model facilities is needed with details of the number and types of equipment, natural gas volumes, pressures and other similar data to determine methane reduction estimates and costs of control.

18. A reduction in methane emissions could be achieved by a wide variety of actions which conserve energy, improve the efficiency of energy use, or convert wastes to energy. These measures reduce methane emissions from energy conversion equipment, waste disposal as well as the whole fuel production and distribution network.

19. Methane emissions can be decreased by reducing the quantities of biodegradable wastes disposed of in landfills or, in the case of woodwaste, disposed of in bee-hive burners. Phase-out of bee-hive burners for woodwaste and use of alternate incinerators or energy systems with more efficient combustion will also reduce methane emissions.

20. Economic, other incentives and regulations have the potential for reducing methane emissions, including taxes on high emitters, rebates for low emitters, emission fees, emissions trading, and command and control strategies. Each of these have advantages and disadvantages, as discussed in the report. A

detailed study of these options would be needed in the context of specific source sectors and subsectors to determine costs and the reduction in methane emissions which could be expected.

21. Control measures were selected from a master list as reasonable for implementation in the short and long-term, with consideration of expected economics and social impacts. A 13% reduction in anthropogenic methane emissions was estimated in the short-term (< 3 yrs). A 27% reduction in anthropogenic emissions was estimated in the long-term (> 10 yrs), relative to emissions in 2005. The net emissions after control (412 kt) in the long-term were found to be 23% lower than those estimated for 1990 (533 kt). No control measures were considered for natural emissions sources. The most important source sector for application of controls is landfills, because it is the dominant emission source. The control measures considered for this source sector included landfill gas recovery and a reduction in the quantities of wastes landfilled.

B. RECOMMENDATIONS

1. Economic barriers to installation of landfilled gas recovery systems should be reviewed.

2. A methane emission model should be developed and verified using landfills in B.C. operating landfill gas recovery systems for subsequent use for analysis of the economic viability of recovery at major landfills in the Province. Data from existing landfill gas recovery systems can be interpreted to determine the appropriateness of the Scholl Canyon model for use in B.C. and to develop default values for the model input parameters.

3. Existing regulations for municipal and industrial landfills should be reviewed and revised, as appropriate, so they yield landfills well suited to landfill gas recovery or similarly effective methane control.

4. Alternatives to incineration and landfilling of woodwastes should be developed, including reduction of waste generation, use for production of wood products or pulp, and use as a fuel.

5. A code of practice should be developed for the owners/operators of natural gas production, processing and transmission of natural gas.

6. A detailed study of methane emissions from the natural gas production, processing, transmission and distribution system should be undertaken which quantifies emissions and determines the cost-effective of control measures.

7. A detailed study should be undertaken of the cost and effectiveness of economic incentives for methane emission control.

8. Use of aerobic or anaerobic manure treatment systems on dairy farms should be encouraged.

9. A more detailed analysis should be done to determine methane emissions from landfills of woodwaste and pulp mill wastes, because of the uncertainty in the preliminary estimates made in this study.

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APPENDIX I

METHANE EMISSIONS FROM LIVESTOCK POULTRY AND WILDLIFE

METHANE EMISSIONS FROM LIVESTOCK POULTRY AND WILDLIFE

A REPORT TO

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METHANE EMISSIONS FROM LIVESTOCK AND POULTRY

In this report the total annual production of methane from live animals and poultry is calculated from the British Columbia populations of the various classes or production groups of these animals and poultry times the individuals annual production of methane gas. The annual production of methane by individual animals was calculated from their digestible energy (DE) intake and the proportion of that energy lost as methane. The annual methane production from poultry was calculate from their metabolizable energy (ME) intake and the proportion of that energy lost as methane. In all cases energy intake was assumed to equal requirements.

Livestock and Poultry Populations

Year 1990

The domestic population for the various classes of livestock in British Columbia for the base year of 1990 was taken from the following sources. Where data was not given for the year of 1990 livestock numbers for 1990 where projected the from previous years population trends.

B.C. Broiler Hatching Egg Sector Profile; December, 1990
B.C. Chicken Sector Profile; February, 1991
B.C. Turkey Sector Profile; November, 1990
B.C. Ministry of Agriculture and Fisheries, Annual Statistics, 1988
B.C. Ministry of Agriculture and Fisheries, B.C. Horse Industry Highlight, 1990
Into the Nineties; Sectoral Profile, Beef Industry Of B.C.; October, 1990

Year 2005

Livestock and poultry populations for the year 2005 where projected from the average annual percentage change in their populations for the period of 1980 to 1990. The resulting factor was then applied to the 1990 population with annual compounding to the year 2005. The beef cattle population has increased by 2% per year over the last ten years. However, it was felt that this growth was not sustainable and in fact growth in this industry would only be 10% to the year 2005. In the case of Sheep, Goats and Horses the population statistics where too uncertain to render a judgement for the future and consequently their 2005 population was taken as the same as 1990. The Hog population of British Columbia over the last ten years has shown large gyrations with no definite trend. There also seems to be some uncertainty about it's future direction. Consequently, no change was projected in it's population to the year 2005.

The resulting annual population percentage change factors used to project populations in the year 2005 are as follows:

Dairy Cattle	1.8%	Lay Hens	0.0%
Beef Cattle	0.6%	Broilers	4.9%
Sheep	0.0%	Roasters	4.9%
Goats	0.0%	Broiler Breeders	4.9%
Hogs	0.0%	Turkeys	3.6%
Horses	0.0%		

Methane Production From Livestock and Poultry

Energy Intake

The DE requirements for the various types of livestock and their production groups where taken from the National Research Council, Nutrient Requirements of: Dairy, 1989; Beef, 1984; Sheep, 1985; Goats, 1981; Swine, 1988; and Horses, 1989.

The ME requirements for poultry were calculate from current industry standards of production. For example lay hens consume 0.113 kg/day containing 2700 kcal ME /kg. which equals 305 kcal ME per day.

The productive criteria used in the calculation the respective DE and ME intake of livestock and poultry is presented in Table 1.

TABLE 1

CRITERIA USED IN THE ESTIMATION OF DIGESTIBLE ENERGY (DE) INTAKE OF LIVESTOCK AND POULTRY

ANIMAL CLASS	ANIMAL WEIGHT KG.	CRITERIA
DAIRY CATTLE		
Lactating	600	PRODUCING 20KG OF 3.5% MILK PER DAY
Dry	600	30 DAYS BEFORE CALVING
Replacements	450	YEARLING HEIFERS GAINING 0.7 KG / DAY
Calves	200	9 MONTH OF AGE GAINING 0.7 KG / DAY
BEEF CATTLE		
Brood Cows	550	DRY PREGNANT HAVING NURSED 4 MONTHS OF YEAR
Bulls	800	MAINTENANCE
Replacements	400	GAINING 0.6 KG / DAY
Feedlot	400	GAINING 1.2 KG / DAY FOR 120 DAYS
Calves	250	GAINING .75 KG / DAY
SHEEP		
Ewes and Rams	50	MAINTENANCE WITH EWES LACTATING 3 MONTHS / YEAR
Replacements	30	GAINING .150 KG / DAY
Market Lambs	30	GAINING .300 KG/DAY FOR 160 DAYS
GOATS		
Milking	50	MEDIUM ACTIVITY PRODUCING 2 KG 4% MILK/DAY
Meat	30	MEDIUM ACTIVITY GROWING AT .150 KG / DAY
Hobby	50	MEDIUM ACTIVITY
HOGS		
Sows	165	PRODUCING 16 PIGS / YEAR
Boars	200	MAINTENANCE
Market	50	GAINING .760 KG/DAY FOR 175 DAYS
POULTRY		
Lay Hens	2	CONSUMING .113 KG FEED/DAY CONTAINING 2700 KCAL ME/KG
Lay Pullets	0.7	CONSUMING 6.8 KG TOTAL FEED CONTAINING 2860 KCAL ME/KG IN 140 DAYS
Market Broilers	2	CONSUMING 3.8 KG TOTAL FEED CONTAINING 3410 KCAL ME/KG IN 46 DAYS
Market Roasters	3.63	CONSUMING 8.7 KG TOTAL FEED CONTAINING 3190 KCAL ME/KG IN 70 DAYS
Broiler Breeders	3.3	HENS CONSUMING .16 KG FEED/DAY CONTAINING 2662 KCAL ME/KG
Breeder replacements	1.1	CONSUMING 11.8 KG TOTAL FEED CONTAINING 2750 KCAL ME/KG IN 154 DAYS
TURKEYS		
Light	4.54	CONSUMING 11.35 KG TOTAL FEED CONTAINING 3190 KCAL ME/KG IN 91 DAYS
Heavy	10	CONSUMING 27.5 KG TOTAL FEED CONTAINING 3080 KCAL ME/KG IN 126 DAYS
HORSES	500	DOING LIGHT WORK

Methane Production As Percent Of Energy Intake

Methane is produced in the intestine of animals by anaerobic microbial fermentation ingested feedstuffs. The methane gas produced is lost to the animal through eructation, respiration and flatulation and represents an energy loss to the animal that does not show up in the faeces. Digestible energy (DE) is the gross energy intake minus that not recovered in the faeces. Thus, the energy lost as methane represents a portion of digestible energy DE. In poultry faeces and urine are excreted together and as a consequence the normal unit of energy requirement in poultry is metabolizable energy (ME). in the case of poultry methane loss represents a portion of ME. Measurement of this loss requires expensive respiration calorimetry apparatus. For this reason, efforts have been made to derive prediction equations that express methane in terms of the caloric value of methane lost as a percentage of energy intake of the total ration (Blaxter and Clapperton, 1965).

The methane production by the individual was calculated as a percent of their digestible energy (DE) intake in the case of mammals or their metabolisable energy (ME) intake in the case of poultry. The percentage factors used where either taken directly from the published literature or where calculated from published calorimetric data. A summarization of this data and the associated references is presented in Appendix Table 1. In consideration of this data it was apparent that feeding corn base rations to ruminants yielded methane levels that were approximately 2 percentage units of DE less than barley-grass-alfalfa based rations. Since ruminant livestock production in British Columbia is based predominantly on barley-grass-alfalfa rations the kcal of methane produced was taken as 9% of the DE intake of cattle, sheep and goats. The amount of methane produced in grammes was then calculated by dividing the kcal of methane produced by 13.23 the caloric value of one gramme of methane. (Report of Sub-Committee on Constants and Factors, European Association For Animal Production, 1965).

For example:
Cow consuming 20000 kcal DE/day produces:
20000 * .09 = 1800 kcal methane/day
1800 /13.23 = 136 gm methane/day

The percent of DE lost as methane was taken as 0.75% for hogs (NRC, 1988) and 3% for horses (Crutzen, Aselmann & Seiler, 1986; Blaxter & Czerkawski, 1966). The percent of ME lost as methane for poultry was taken as 0.2% for poultry (Gaseway, 1976).

The annual individual production of methane was calculated as the individuals daily production of methane times the normal life span of that animal during the year. Thus feedlot cattle produce 185.7 gm methane/day for 120 days (Table 1) which equals 22.28 kg methane per animal per year and growing hogs 4.83 gm/day for 172 days etc. This approach rendered the methane production data compatible with the population statistics which originated primarily from marketing records.

The data on the daily and annual production of methane by the various productive groups of livestock and poultry is presented in Appendix Table 2.

Methane Emissions Year 1990

The total annual methane production for these various productive groups of livestock and poultry based on populations and their annual methane production is presented in Table 2. This figure was then multiplied by the number of feedlot cattle to give the total annual production of methane for that group of livestock ie. 743.3 tonnes/year.

TABLE 2

ANNUAL METHANE PRODUCTION FROM DOMESTIC LIVESTOCK AND POULTRY

ANIMAL CLASS		ANIMAL NUMBERS	ANNUAL PRODUCTION KG/ANIMAL	TOTAL PRODUCTION TONNES/YEAR
********************		*********	**********	*************
DAIRY CATTLE				
	Lactating	65570	110.568	7249.9
	Dry	12822	65.129	835.1
	Replacements	28000	67.438	1888.3
	Calves	28000	32.279	903.8
BEEF CATTLE				
	Brood Cows	228000	50.330	11475.3
	Bulls	11000	57.109	628.2
	Replacements	42000	46.680	1960.6
	Feedlot	33354	22.286	743.3
	Calves	200000	42.956	8591.2
SHEEP				
	Ewes and Rams	25400	7.821	198.7
	Replacements	5000	6.952	34.8
	Market Lambs	4500	3.701	16.7
GOATS				
	Milking	10000	16.313	163.1
	Meat	10000	9.187	91.9
	Hobby	10000	8.715	87.2
HOGS				
	Sows	22700	1.657	37.6
	Boars	1500	1.304	2.0
	Market	340176	0.845	287.5
POULTRY				
	Lay Hens	2407652	0.017	40.7
	Lay Pullets	2407652	0.003	7.1
	Market Broilers	46558062	0.002	91.6
	Market Roasters	2244938	0.004	9.8
	Broiler Breeders	451000	0.023	10.6
	Breeder replacements	451000	0.005	2.3
TURKEYS				
	Light	819000	0.006	4.5
	Heavy	1131000	0.013	14.5
HORSES		75000	16.553	1241.5
			TOTAL	36617.5

The range of methane production from livestock and poultry for the year 1990 is presented in Table 3.

TABLE 3

RANGE ANNUAL METHANE PRODUCTION FROM DOMESTIC LIVESTOCK AND POULTRY

ANIMAL CLASS	RANGE % DE INTAKE AS METHANE	LOW METHANE PRODUCTION TONNES/YEAR	HIGH METHANE PRODUCTION TONNES/YEAR
DAIRY CATTLE			
Lactating	6.7-14.3	5397.2	11519.3
Dry	6.7-14.3	621.7	1326.9
Replacements	6.7-14.3	1405.7	3000.2
Calves	6.7-14.3	672.8	1436.1
BEEF CATTLE			
Brood Cows	6.7-14.3	8542.7	18233.0
Bulls	6.7-14.3	467.7	998.1
Replacements	6.7-14.3	1459.5	3115.1
Feedlot	6.7-14.3	553.4	1181.0
Calves	6.7-14.3	7291.0	15561.4
SHEEP			
Ewes and Rams	8.0-13.6	176.6	300.2
Replacements	8.0-13.6	30.9	52.5
Market Lambs	8.0-13.6	14.8	25.2
GOATS			
Milking	8.0-13.6	145.0	246.5
Meat	8.0-13.6	81.7	138.8
Hobby	8.0-13.6	77.5	131.7
HOGS			
Sows	.4-1.0	20.1	50.2
Boars	.4-1.0	1.0	2.6
Market	.4-1.0	153.3	383.4
POULTRY			
Lay Hens	.2-.4	40.7	81.3
Lay Pullets	.2-.4	7.1	14.2
Market Broilers	.2-.4	91.6	183.2
Market Roasters	.2-.4	9.8	19.7
Broiler Breeders	.2-.4	10.6	21.2
Breeder replacements	.2-.4	2.3	4.5
TURKEYS			
Light	.2-.4	4.5	9.0
Heavy	.2-.4	14.5	29.0
HORSES	3.0-4.0	1241.5	1655.3
	TOTAL	28535.2	59719.6

Methane Emissions Year 2005

The estimated methane production of livestock and poultry in the year 2005 is presented in Table 4.

TABLE 4

PROGECTED YEAR 2005 METHANE PRODUCTION FROM DOMESTIC LIVESTOCK AND POULTRY

ANIMAL CLASS		ANIMAL NUMBERS	ANNUAL METHANE PRODUCTION KG/ANIMAL	TOTAL METHANE PRODUCTION TONNES/YEAR
DAIRY CATTLE				
	Lactating	85688	110.568	9474.3
	Dry	16756	65.129	1091.3
	Replacements	36591	67.438	2467.6
	Calves	36591	32.279	1181.1
BEEF CATTLE				
	Brood Cows	250800	50.330	12622.8
	Bulls	12100	57.109	691.0
	Replacements	46200	46.680	2156.6
	Feedlot	36690	22.286	817.7
	Calves	220000	42.956	9450.3
SHEEP				
	Ewes and Rams	25400	7.821	198.7
	Replacements	5000	6.952	34.8
	Market Lambs	4500	3.701	16.7
GOATS				
	Milking	10000	16.313	163.1
	Meat	10000	9.187	91.9
	Hobby	10000	8.715	87.2
HOGS				
	Sows	22700	1.657	37.6
	Boars	1500	1.304	2.0
	Market	340176	0.845	287.5
POULTRY				
	Lay Hens	2407652	0.017	40.7
	Lay Pullets	2407652	0.003	7.1
	Market Broilers	95553852	0.002	188.0
	Market Roasters	4391782	0.004	19.2
	Broiler Breeders	925614	0.023	21.7
	Breeder replacements	925614	0.005	4.6
TURKEYS				
	Light	1400215	0.006	7.7
	Heavy	1933630	0.013	24.8
HORSES		75000	16.553	1241.5
			TOTAL	42427.4

METHANE EMISSIONS FROM MANURE 1990

Methane is produced only under anaerobic conditions by bacteria that require a wet and warm environment. The environment necessary for the production of methane from manure is only encountered when the manure is stored wet in lagoons or deep pits. In British Columbia manure from animals and poultry other then dairy cattle, feedlot cattle, hogs and lay hens and pullets is either too dry to start with and stored that way or is dropped at pasture or range where it dries naturally under aerobic conditions. For this reason only manure that may be handled and stored anaerobically was considered to produce methane.

Methane is produced from the "Volatile Solids" or organic matter in the manure. The amount of volatile solids produced by the various classes of livestock and poultry was calculated from their populations and factors for volatile solids production published by The Society for Engineering in Food and Agriculture, American Society of Agricultural Engineers, 1989. The amount of methane produced from the volatile solids was then calculated by multiplying by 186.16 gm of methane/kg of volatile solids produced from cattle and hogs and 200.48 gm of methane/kg of volatile solids produced from poultry (Safley and Westerman, 1988). The results of these calculations are presented in Table 5.

TABLE 5

ESTIMATED METHANE PRODUCTION FROM MANURE FROM DOMESTIC LIVESTOCK AND POULTRY

ANIMAL CLASS	ANIMAL NUMBERS	VOLATILE SOLIDS PRODUCTION KG/DAY	VOLATILE SOLIDS PRODUCTION TONNES/YEAR	POTENTIAL METHANE PRODUCTION TONNES/YEAR
DAIRY CATTLE				
Lactating	65570	6.000	143598.3	26732.3
Dry	12822	6.000	28080.2	5227.4
Replacements	28000	4.500	45990.0	8561.5
Calves	28000	2.000	20440.0	3805.1
BEEF CATTLE				
Brood Cows	228000	3.960	329551.2	AEROBIC
Bulls	11000	5.760	23126.4	AEROBIC
Replacements	42000	2.880	44150.4	AEROBIC
Feedlot	33354	2.880	11527.1	2145.9
Calves	200000	1.800	131400.0	AEROBIC
SHEEP				
Ewes and Rams	25400	0.460	4264.7	AEROBIC
Replacements	5000	0.276	503.7	AEROBIC
Market Lambs	4500	0.276	198.7	AEROBIC
GOATS				
Milking	10000	0.460	1679.0	AEROBIC
Meat	10000	0.276	1007.4	AEROBIC
Hobby	10000	0.460	1679.0	AEROBIC
HOGS				
Sows	22700	1.403	11620.4	2163.3
Boars	1500	1.700	930.8	173.3
Market	340176	0.425	25300.6	4710.0
POULTRY				
Lay Hens	2407652	0.024	21091.0	4228.3
Lay Pullets	2407652	0.008	2831.4	567.6
Market Broilers	4.7e+07	0.017	36408.4	AEROBIC
Market Roasters	2244938	0.031	4848.7	AEROBIC
Broiler Breeders	451000	0.039	6469.4	AEROBIC
Breeder replacements	451000	0.013	916.8	AEROBIC
TURKEYS				
Light	819000	0.041	3078.0	AEROBIC
Heavy	1131000	0.091	12968.0	AEROBIC
HORSES	75000	5.000	136875.0	AEROBIC
		TOTAL	1050534.7	58314.6

The estimated methane production from manure from livestock and poultry in the year 2005 is presented in Table 6.

TABLE 6

PROGECTED METHANE PRODUCTION FROM MANURE FROM DOMESTIC LIVESTOCK AND POULTRY IN THE YEAR 2005

ANIMAL CLASS	ANIMAL NUMBERS	VOLATILE SOLIDS PRODUCTION KG/DAY	VOLATILE SOLIDS PRODUCTION TONNES/YEAR	POTENTAL METHANE PRODUCTION TONNES/YEAR
********************	*********	************	**************	************
DAIRY CATTLE				
Lactating	85688	6.000	187656.7	34934.2
Dry	16756	6.000	36695.6	6831.3
Replacements	36591	4.500	60100.7	11188.3
Calves	36591	2.000	26711.4	4972.6
BEEF CATTLE				
Brood Cows	306858	3.960	443532.6	AEROBIC
Bulls	14800	5.760	31115.5	AEROBIC
Replacements	56526	2.880	59420.1	AEROBIC
Feedlot	44890	2.880	15514.0	2888.1
Calves	220000	1.800	144540.0	AEROBIC
SHEEP				
Ewes and Rams	25400	0.460	4264.7	AEROBIC
Replacements	5000	0.276	503.7	AEROBIC
Market Lambs	4500	0.276	198.7	AEROBIC
GOATS				
Milking	10000	0.460	1679.0	AEROBIC
Meat	10000	0.276	1007.4	AEROBIC
Hobby	10000	0.460	1679.0	AEROBIC
HOGS				
Sows	22700	1.403	11620.4	2163.3
Boars	1500	1.700	930.8	173.3
Market	340176	0.425	25300.6	4710.0
POULTRY				
Lay Hens	2407652	0.024	21091.0	4228.3
Lay Pullets	2407652	0.008	2831.4	567.6
Market Broilers	95553852	0.017	74723.1	AEROBIC
Market Roasters	4391782	0.031	9485.6	AEROBIC
Broiler Breeders	925614	0.039	13277.5	AEROBIC
Breeder replacements	925614	0.013	1881.6	AEROBIC
TURKEYS				
Light	1400215	0.041	5262.4	AEROBIC
Heavy	1933630	0.091	22171.0	AEROBIC
HORSES	75000	5.000	136875.0	AEROBIC
		TOTAL	1340069.6	72656.9

METHANE EMISSIONS FROM WILDLIFE 1990

In this report methane production was only considered for wildlife ruminants due to the ruminants being the major producer of methane in animals and the lack of population statistics and information on methane production in other wildlife species.

Wildlife Population

Year 1990

Population statistics for the various classes of wildlife in British Columbia was supplied by the Fish and Wildlife Branch of the B.C. Ministry of Environment, Victoria, B.C.

Year 2005

The Fish and Wildlife Branch of the Ministry of Environment are projecting that through their habitat enhancement programmes wildlife numbers will increase by 10 to 20 percent in the next 15 years. On the basis of this information wildlife numbers where projected to have increased by 15 percent by 2005.

Energy Intake

The energy requirements of wildlife species is not well defined as it is with domestic animals. However, it has long been established that basal metabolism of mammals in kcal/day may be expressed by the equation 70 * Body Weight(kg) to the 0.75 power. For this paper wildlife where considered to exist at maintenance and the above equation was increased by 20% to account for activity. Thus the DE intake of wildlife expressed as Mcal/day was calculated as .084*W*0.75 power, where W = Body Weight in KG.

Methane Production As Percent Of Energy Intake

In leu of data to the contrary, the methane production of wildlife included in this report was taken as the same percent of DE intake as that of the domestic ruminant (9% of DE intake). The calculations of the annual methane production per animal based on the DE intake of wildlife is presented in Appendix Table 3.

Methane Emissions Year 1990

The total annual methane production for the various types of wildlife are presented in Table 7.

TABLE 7

ANNUAL METHANE PRODUCTION FROM WILDLIFE RUMINANTS

ANIMAL CLASS	ANIMAL NUMBERS	ANNUAL METHANE PRODUCTION KG/YEAR	TOTAL METHANE PRODUCTION TONNES/YEAR
**************	*********	************	**************
MOOSE	175000	17.238	3016.61
ELK	40000	13.892	555.70
CARIBOU	14000	9.383	131.36
SHEEP			
Thinhorn	12000	5.048	60.57
Bighorn	7700	7.084	54.55
MOUNTAIN GOAT	56000	6.094	341.29
DEER			
Black-tailed	350000	5.048	1766.63
White-tailed	48000	5.048	242.28
		TOTAL	6169.00

The range of methane production from wildlife for the year 1990 presented in table 8.

TABLE 8

RANGE ANNUAL METHANE PRODUCTION FROM WILDLIFE RUMINANTS

ANIMAL CLASS	RANGE % DE INTAKE AS METHANE	LOW METHANE PRODUCTION TONNES/YEAR	HIGH METHANE PRODUCTION TONNES/YEAR
*************	************	**************	************
MOOSE	6.7-14.3	2245.700	4793.10
ELK	6.7-14.3	413.700	882.90
CARIBOU	6.7-14.3	97.800	208.70
SHEEP			
Thinhorn	6.7-14.3	45.100	96.20
Bighorn	6.7-14.3	40.600	86.70
MOUNTAIN GOAT	6.7-14.3	254.100	542.30
DEER			
Black-tailed	6.7-14.3	1315.200	2807.00
White-tailed	6.7-14.3	180.400	385.00
	TOTAL	4592.6	9801.90

Methane Emissions Year 2005

The estimated annual methane production from wildlife in the year 2005 is presented in Table 9.

TABLE 9

PROJECTED METHANE PRODUCTION FROM WILDLIFE
IN THE YEAR 2005

ANIMAL CLASS	ANIMAL NUMBERS	ANNUAL METHANE PRODUCTION KG/YEAR	TOTAL METHANE PRODUCTION TONNES/YEAR
Moose	201250	17.238	3469.11
Elk	46000	13.892	639.05
Caribou	16100	9.383	151.07
SHEEP			
Thinhorn	13800	5.048	69.66
Bighorn	8855	7.084	62.73
Mountain Goat	64400	6.094	392.48
DEER			
Black-tailed	402500	5.048	2031.63
White-tailed	55200	5.048	278.62
		TOTAL	7094.35

REDUCING METHANE EMISSIONS

LIVE ANIMALS

Productivity Enhancement

Dairy

1. The use of Bovine Somatotropin (BST) improve milk production and the efficiency of milk production by 10-15%. Commercial availability of BST still awaits legislation and public acceptance.

Beef and Sheep

1. The use of hormone implants increase rate and efficiency of gain by 10-15%.

2. The greater use of ionophores can improve growth and feed conversion in cattle and sheep by at least 10%. Reduction in methane is due to a reduction in feed intake rather than the manipulation of fermentation as monensin reduced methane production per unit of DE intake only for a few days before adaptation took place and lasalocid had no effect on methane production per unit of DE intake (Rumpler & Johnson 1985)

3. Feeding, injecting or implanting BST or Beta-Antagonist may improve growth and feed conversion by 10-15%. Use of these productivity enhancers awaits technical development and legislation.

Feeding Management

Dairy, Beef, Sheep and Goats

1. High grain rations to increase the proportion of propionic to acetic acid in the rumen. Dairy men are already feeding up to 60% grain in their rations. Limit of grain feeding due to the tendency to over-fatten and reduce butter fat production with high propionate to acetate ratios.

2. Feeding of long chain free-fatty acids to ruminants may reduce methane production by approximately 18-25% (Blaxter & Czerkawski 1966). Free-fatty acids from refining of Canola oil are available commercially.

3. Feeding of corn vs barley in the grain ration would appear to reduce methane production by 20-25%. Grain corn of itself is expensive in British Columbia due to it not being grown here. Development of earlier maturing varieties could lead to its extensive cultivation in British Columbia. Corn silage is extensively grown on British Columbian dairy farms. Extension of this practice should be encouraged particularly in the interior and on beef operations.

4. The feeding of alfalfa vs orchard grass hay appear to reduce methane production by about 16% (Verga et.al., 1985). due to the wet conditions on the Lower Mainland and Vancouver Island alfalfa is not grown. However, dairy farmers on the Lower Main land and Vancouver Island could be encouraged to grow more corn silage and feed imported alfalfa hay from the Interior or Washington.

5. The feeding of properly formulated livestock minerals should be encouraged so as to prevent productivity inhibiting deficiencies in such micro-minerals as copper, zinc and selenium. this is most important in the dry period of dairy cows. Continuous feeding of properly formulated livestock mineral has been shown to increase growth rate of cattle at pasture in Alberta by 10-15%. Fertility in cattle and sheep and calf survival have been increased from 50-95%.

6. Feeding of adequate levels of protein may prevent production of excess amounts of methane per unit of DE intake. Terada et.al., 1985 has demonstrated in both sheep and cattle that feeding of low protein (5-8%) led to a 45% increase in methane production per unit of DE intake.

7. The feeding of by-pass proteins and fats increase level and efficiency of milk production. Protein by-pass may be improved by feeding more animal source proteins such as meat meal, blood meal, feather meal and fish meal. Other protein sources such as brewers and distillers grains also have good by-pass characteristics. Feeding of whole cotton seed improves the by-pass of both protein and fat.

Manure Handling

1. promote the development and use of anaerobic digestion systems that economically collect and store methane gas for use either at the site of production or elsewhere.

2. Promote the development and use of economical aerobic digestion systems for use in intensive housing and management livestock systems.

3. Reduce the amount of fermentable volatile solids exposed to prolonged anaerobic conditions through the use of solids separators combined with composting or more frequent disposal on the land.

MANURE TREATMENT

AEROBIC DIGESTION

Farm Type

200 cow dairy farm or 200 sow hog farm

Existing Manure Handling Facilities

Daily collection pit and lagoon

Description

Daily manure production is pumped from collection pit to a continuous flow aerobic digester for treatment for seven days prior to discharge to the farm lagoon. A 200 cow dairy farm producing 14.7 Tonnes/day of 14% solids manure or a 200 sow hog farm producing 16.6 Tonnes/day of 13% solids manure would require two 6 meter diameter times 5 meter height tanks equipped with aeration diffuser manifolds on their bottoms. Both manifold would be connected to a single 10 hp air blower which would supply air to the manifold at 3.2 to 3.6 Kg pressure. The suppernant would be discharged to the farm lagoon by gravity. Maintenance requirements would consist of lubricating the air blower once a month at an estimated time requirement of one half hour per month.

Capital Cost

2 Aeration Tanks @ $45,000 ea.	90,000
2 Cement Slabs @ $1500 ea.	3,000
1 10hp Air Blower	8,000
Air Diffusers Pipes & Valves	5,000
Miscellaneous	4,000
TOTAL	110,000

Operating Cost Per Month

Electricity @ $1.00/hp/day	300
Labour 1/2 hour @ $10/hour	5
Maintenance Oil 1 litre	3
TOTAL	308

Benefits

Although the exact figure under B.C. conditions is not known it is estimated that aeration for seven days could reduce methane emissions by at least 70% (Czerkawski and Breckenridge, 1969). Further, it has been shown that aeration for only two days has reduced the odour producing volatile solids of hog manure by 32% (Van Kleek, 1991 Personal Communication) without reducing the amount and value of the fertilizer minerals potassium and phosphorus.

Impact

The net impact of aeration of manure to reduce or eliminate methane emissions from this source would be an additional cost over and above current cost of manure disposal of approximately $ 550 per cow or sow in capital cost and $ 1.50 in operating cost.

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APPENDIX TABLE 1

METHANE PRODUCTION FROM LIVESTOCK AND POULTRY
PERCENT OF DE INTAKE

SPECIES	RATION	LEVEL	CH4 AVE.	CH4 LOW	CH4 HIGH	COMMENTS	REFERENCES
Steers	70C+20CS+10BG	2+	7.91	7.48	8.67		Rumpler,Johnson&Bates1986
Steers	70C+20CS+10BG	2+	7.65	7.12	8.18	Control	Rumpler & Johnson 1985
Steers	70C+20CS+10BG	2+	6.85	6.65	7.25	2.5% Na	Rumpler & Johnson 1985
Steers	70C+20CS+10BG	2+	7.6	6.38	8.25	Monensin	Rumpler & Johnson 1985
Steers	70C+20CS+10BG	2+	7.36	6.65	7.78	Lasalocid	Rumpler & Johnson 1985
Steers	70C+30CS	1-2	7.8	7.6	8.4	Control	Johnson & Wedegaertner1985
Steers	70C+30CS	1-2	5.7	5.4	5.9	Monensin	Johnson & Wedegaertner1985
Steers	100Alf	1+	8.42	8.09	8.75		Varga et.al. 1985
Steers	100 Orch.G.	1+	9.82	9.72	9.91		Varga et.al. 1985
Steers	85B+15Conc.	1+	13.0	12.6	13.4	No rough.	Whitelaw et.al. 1984
Steers	87WS+13Conc.	1+	10.75	10.7	10.8	+NH3	Birkelo,Johnson&Ward1986
Cows	84RS+15[illegible]+S	1	13.53	13.4	13.6	Prot5-8%	Terada et.al. 1985
Cows	GH+Conc.	1	9.28	7.5	10.5	Prot13-14%	Terada et.al. 1985
Caws	100GH	1+	13.58	12.8	14.3		Van Es,Brouwer & Nijkamp,1965
C.Lac.	100%Alf.	1-2	9.56	9.3	10.7		Flatt,Coppock&Moore1965
C.Lac	25C+75Alf	1-2	9.78	9.1	10.8		Flatt,Coppock&Moore1965
C.Lac	50C+50Alf	1-2	9.27	8.9	10.3		Flatt,Coppock,Moore1965
C.Lac	40C+60Alf	2+	7.82	7.7	7.94		Flatt,et.al 1967
C.Lac	60C+40Alf	2+	6.05	5.93	6.17		Flatt,et.al. 1967
C.Lac	80C+20Alf	2+	4.99	4.87	5.11		Flatt,et.al. 1967
Sheep	Mixed	1+	8.07	6.2	10.8		Blaxter&Clapperton1965
Sheep	Grass	2	10.37	10.2	10.7		Ekern,Blaxter&Sawers1965
Sheep	Grass	1	8.0	6.7	9.3		Grass+Clover McC. Graham 1965
Sheep	Alf Chaff	1-	9.1	7.54	11.3	3.8%prot	Murry,Bryant&Leng1978
Sheep	RS+B+S	1	13.57	13.1	13.9	Prot5-8%	Terada et.al.1985
Sheep	GH+Conc.	1	8.59	6.48	10.1	Prot13-14%	Terada et.al. 1985
Goats	RS+B+S	1	13.12	13.1	13.3	Prot5-8%	Terada et.al. 1985
Goats	GH+Conc.	1	9.2	9.1	9.4	Prot13-14%	Terada et.al. 1985
Goats	GH+Conc.	2-3	8.23	6.96	9.46	Lactating	Armstrong & Blaxter1965
Hogs	?	?	0.75	0.5	1.0		NRC, 1988
Hogs	?	?	0.65	0.4	0.9		Crutzen,Aselmann&Seiler1986
Poultry	?	?	0.2	0.2	0.4		Gaseway 1976
Horses	?	?	3.5	3.0	4.0		Crutzen,Aselmann&Seiler1986
Horses	?	?	2.75	2.5	3.0		Blaxter & czerkawski 1966

Alf=alfalfa
B=Barley
BG=Brewers Grains

Conc.=Grain+Prot. Concentrate
C=Corn
CS=Corn Silage

GH=Grass Hay
Orch.G.=Orchard Grass
RS=Rice Straw

S=Soybean Meal
WS=Wheat Straw

APPENDIX TABLE 2

METHANE PRODUCTION OF DOMESTIC LIVESTOCK AND POULTRY

ANIMAL CLASS	ENERGY INTAKE MCAL/DAY	ENERGY INTAKE AS METHANE %	METHANE PRODUCTION GMS/DAY
DAIRY CATTLE			
Lactating	44.530	9.00	302.925
Dry	26.230	9.00	178.435
Replacements	27.160	9.00	184.762
Calves	13.000	9.00	88.435
BEEF CATTLE			
Brood Cows	20.270	9.00	137.891
Bulls	23.000	9.00	156.463
Replacements	18.800	9.00	127.891
Feedlot	27.300	9.00	185.714
Calves	17.300	9.00	117.687
SHEEP			
Ewes and Rams	3.150	9.00	21.429
Replacements	2.800	9.00	19.048
Market Lambs	3.400	9.00	23.129
GOATS			
Milking	6.570	9.00	44.694
Meat	3.700	9.00	25.170
Hobby	3.510	9.00	23.878
HOGS			
Sows	8.010	0.75	4.541
Boars	6.300	0.75	3.571
Market	8.520	0.75	4.830
POULTRY			
Lay Hens	0.306	0.20	0.046
Lay Pullets	0.139	0.20	0.021
Market Broilers	0.283	0.20	0.043
Market Roasters	0.414	0.20	0.063
Broiler Breeders	0.425	0.20	0.064
Breeder replacements	0.215	0.20	0.033
TURKEYS			
Light	0.400	0.20	0.060
Heavy	0.673	0.20	0.102
HORSES	20.000	3.00	45.351

APPENDIX TABLE 3

METHANE PRODUCTION OF WILDLIFE RUMINANTS

ANIMAL CLASS	LIVE WEIGHT KG	DIGESTIBLE ENERGY INTAKE MCAL/DAY	DIGESTIBLE ENERGY INTAKE AS METHANE %	METHANE PRODUCTION GMS/DAY	METHANE PRODUCTION KG/YEAR
MOOSE	360	6.942	9.00	47.227	17.238
ELK	270	5.595	9.00	38.061	13.892
CARIBOU.	160	3.779	9.00	25.707	9.383
SHEEP					
Thinhorn	70	2.033	9.00	13.829	5.048
Bighorn	110	2.853	9.00	19.409	7.084
MOUNTAIN GOAT	90	2.454	9.00	16.697	6.094
DEER					
Black-tailed	70	2.033	9.00	13.829	5.048
White-tailed	70	2.033	9.00	13.829	5.048

APPENDIX II-A

VEHICLE TYPE DEFINITIONS

APPENDIX II-B

CALCULATION OF METHANE EMISSIONS FROM GAS AND DIESEL VEHICLES

The following definitions of vehicle types were taken from:

> Environmental Applications Group Ltd. et al, "1985 Lower Mainland Emission Inventory, D: Mobile Sources, Volume 2: Methodology", prepared for GVRD Pollution Control, May 1988.

LDGV - light duty gasoline vehicles; any gasoline fueled motor vehicle designated primarily for transportation of persons and having a seating capacity of 12 persons or fewer.

LDGT1 - light duty gasoline powered trucks 1; any gasoline fueled motor vehicle designated primarily for transportation of property and rated at 2722 kg (6000 lb) GVW or less.

LDGT2 - light duty gasoline powered truck 2; any gasoline fueled motor vehicle designated primarily for transportation of property and rated between 2722 kg (6001 lb) and 3856 kg (8500 lb) GVW inclusive.

HDGV - heavy duty gasoline powered vehicles, any gasoline fueled motor vehicle designated primarily for the transportation of property and rated at more than 3856 kg (8500 lb) GVW, or designated primarily for transportation of persons and having a capacity of more than 12 persons.

LDDV - light duty diesel powered vehicles; any diesel fueled motor vehicle designated primarily for transportation of persons and having a capacity of 12 persons or fewer.

LDDT - light duty diesel powered trucks; any diesel fueled motor vehicle designed primarily for transportation of property and rated at 3856 kg (8500 lb) or less.

HDDV - heavy duty diesel powered vehicles, any diesel fueled motor vehicle designated primarily for transportation of property and rated at more than 3856 kg (8500 lb) GVW, or designated for transportation of persons and having a capacity of more than 12 persons.

MC - motorcycles; any motor vehicle designed to travel with not more than three wheels in contact with the ground, and weighing less than 680 kg (1500 lb).

GASOLINE VEHICLES

Vehicle Type	# in Active Fleet	VkmT per veh.yr	Ave.fuel Consump. (l/100km)	Total VkmT	Fuel Consumed (litres)	Fuel Consumed (PJ)	Vehicle Dist'n (%)
LDGV	1,391,422	13920	13.3	19,368,594,240	2,576,023,034	89.28	74.72%
LDGT 1	433,807	17600	18	7,635,003,200	1,374,300,576	47.63	23.30%
LDGT 2	16,118	17600	18	283,676,800	51,061,824	1.77	0.87%
HDGV	2,719	20000	25.5	54,380,000	13,866,900	0.48	0.15%
MC	18,163	2800	7.1	50,856,400	3,610,804	0.13	0.98%
	1,862,229			27,392,510,640	4,018,863,138	139.29	100.00%
Gasoline		Energy content TJ/ML		34.66	139.29	PJ/yr	

Base Quantity	Units	Emission Factors	Units	Tot.CH4 Emissions tonnes/yr	
139.2938	PJ	47.7	tonnes/PJ	6,644.31	Adhoc
1.39E+08	GJ	36	g/GJ	5,014.58	CEC

DIESEL VEHICLES

Vehicle Type	# in Active Fleet	VkmT per veh.yr	Ave.fuel Consump. (l/100km)	Total VkmT	Fuel Consumed (litres)	Fuel Consumed (PJ)	Vehicle Dist'n (%)
LDDV	19,446	13920	10	270,688,320	27,068,832	1.05	26.16%
LDDT	14,798	17600	11.3	260,444,800	29,430,262	1.14	19.91%
HDDT	40,090	82400	49.4	3,303,416,000	1,631,887,504	63.12	53.93%
	74,334			3,834,549,120	1,688,386,598	65.31	100.00%
	Diesel	Energy content TJ/ML		38.68	65.31	PJ/yr	

Base Quantity	Units	Emission Factors	Units	Tot.CH4 Emissions tonnes/yr	
65.30679	PJ	4.36	tonnes/PJ	284.74	Adhoc
65306794	GJ	2	g/GJ	130.61	CEC

APPENDIX II-C

CALCULATION OF CH_4 EMISSION FACTOR FOR INCINERATION

Woodwaste Incineration:

THC ≡ Total Hydrocarbons

THC emission from woodwaste incinceration = 11 kg/ODtonnes (BHLA)

Calculation of methane fraction in THC

For Boilers:	VOC	0.7 kg/t
	CH_4	0.15 kg/t
	Total	0.85

∴ Methane wt. fraction ≃ 0.18

Forest Fires: Methane fraction ≃ 0.1

Therefore, expect woodwaste incinerator somewhere between these two extremes.

Assume $(0.1 + 0.18)/2 = 0.14$

Emission factor (woodwaste Incineration)

11 kg/ODt x 0.14 = 1.54 kg CH_4/ODt x 1 ODt/20 GJ = 0.077 kg CH_4/GJ

= 77 tonnes CH_4/PJ

APPENDIX III

METHANE INVENTORY FOR LANDFORMS IN BRITISH COLUMBIA

METHANE INVENTORY FOR LANDFORMS IN BRITISH COLUMBIA

For

B.H. Levelton & Associates Ltd.

Project Number 91-010

June, 1991

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1.0
INTRODUCTION

STUDY BACKGROUND

This study has been carried out by **Talisman Land Resource Consultants** at the request of B.H. Levelton and Associates Ltd. The objective of the study was to prepare an inventory of methane emission and uptake for landforms in British Columbia, based on available information.

The project was carried out by Dr. William Price, P.Ag.

METHODOLOGY

Data was collected from a variety of sources including published books, government reports and scientific journals. In addition contact was made with persons likely to be carrying out relevant research or possessing unpublished information. A list of the persons contacted is given in Appendix 1. In addition to valuable opinions and suggestions, the personal contacts also yielded a number of valuable unpublished sources of information. These along with published documents reviewed are listed in Appendix 2.

2.0
METHANE EMISSION

Methane production or methanogenesis is a reductive process carried out by bacteria under highly anaerobic conditions. Methanogenesis has been measured in waterlogged soils and in aquatic and freshwater sediments, environments with organic matter present under strong reducing conditions.

WETLANDS

Annual Emission Rates

In the past 10 years a number of researchers have measured methane emission from northern wetlands (Table 1). However, considerable uncertainty still exists as to the average annual emission rate from this source. This uncertainty results from the great variability in wetlands themselves and in important climatic factors. All researchers concur that methane emission rates show significant seasonal and spatial variability. Part of the reason for this is that methane release often occurs as an episodic event, such as the release of bubbles. In the Virginia swamp studied by Wilson *et al.* (1989), ebullition (bubbling) accounted for 34% of the methane release.

Given the great seasonal variability, long term studies are required in order to predict annual emission rates. For example, in the Virginia swamp, the maximum methane release occurred in early spring and late summer, while in a variety of Swedish tundra wetlands the higher methane fluxes occurred in July and autumn.

Many researchers have speculated that their studies missed a flush of methane emission after ice melt. Measurements by Moore and Knowles (1990) show that the highest emission rates often occur at the spring thaw, and various authors have speculated that methane displaced during the freezing of wetlands (Nisbet, 1989a; Svensson and Rosewall, 1984) may be released to the atmosphere when the ice melts. On one arctic tundra site, Whalen and Reeburgh (1988) found over 40% of annual methane emission occurred during the winter. Other wetlands behave differently. Naiman *et al.* (1991) calculated winter evasion rates from beaver ponds in Minnesota from the average rates soon after ice-melt and just before heavy ice formation. Their calculations showed the winter production was less than 10% that of the summer. Spring and fall emissions were undetectable in all the wetland sites studied by Vitt *et al.* (1990) in boreal Alberta.

In a wide range of wetlands, Svensson and Rosewall (1984) found that the highest methane production occurred 10 to 15 cm below the surface, the depth at which the Eh was at its lowest value. Methane fluxes varied widely in seemingly homogeneous areas, an observation thought to result from different subsoil reduction potentials and from the heterogeneity of the substrate. Svensson and Rosewall (1984) concluded that the rate of methane release was primarily controlled by the moisture and nutritional status. Correlations with temperature were only noted under continually flooded mineraltrophic conditions.

Various authors have noted different correlations between site factors and methane release. In Minnesota beaver ponds, Naiman *et al.* (1991), found that temperature and redox potential were the variables most strongly correlated with methane emission. The unimportance of total carbon was thought to indicate that the system was not substrate limited. It may also suggest that total carbon had little influence on carbon availability.

The importance of wetland type in determining annual methane emission has been shown in the Canadian studies by Vitt *et al.* (1990) and Moore and Knowles (1990). Vitt *et al.* (1990) found that the relative magnitude of annual methane emission was beaver pond > marsh > rich fen > poor fen, with negligible emission from the bog (descriptions of wetland types are given in Appendix C). Similar magnitudes and relative differences were found in the fens and bogs studied by Moore and Knowles (1990) in Quebec and by Whalen and Reeburg (1988) in Alaska. Notably, permafrost appears to have little effect on methane emission.

Rates of annual methane emission measured in the two Canadian and the Alaska studies are significantly lower than the wetland emission factors used by Matthews and Fung (1988) and Jaques (1991) to predict total methane emission from wetlands (Table 2). These emission factors are based on the early research (Harris *et al.*, 1985; Sebacher *et al.*, 1986; Frill *et al.*, 1988). The greatest differences are for bogs, which had formerly been thought to have similar emission rates to fens. Higher emission rates obtained in the earlier research may be an artifact of the measuring technique or from confining sampling to the hotter months. An additional factor may have been the selection of productive ponded micro-sites. Moore and Knowles (1990) noted up to a hundred times higher methane emission from small waterlogged depressions and pools. As is often the case during the summer, when the water table drops below the surface, methane produced in anoxic subsoil is oxidized in the topsoil. Consequently, methane generation can vary markedly between high and low terrain and between wet and dry years.

Moore and Knowles' (1990) conclusions about the productivity of shallow ponds concur with the data of Vitt *et al.* (1990) for beaver ponds. Beaver ponds contribute to methane emission by the following:

TABLE 1
A SUMMARY OF FIELD MEASUREMENTS OF METHANE EMISSION FROM WETLANDS

	Daily Emission ($mg\ m^{-2}\ day^{-1}$)	Annual Emission ($g\ m^{-2}\ yr^{-1}$)	Duration of Study
Temperate to Low Subarctic (Moore, personal communication)			
- coastal marsh	-	0.1-40	
- hummock	-	0.1-2	
- hollow	-	0.1-3	
- forest margin	-	0.1-1	
- fen margin	-	0.3-10	
- fen	-	0.5-11	
- string	-	0.6-2	
- degrading pool	-	1-11	
- swamp	-	1-5	
- bog	-	0.1	
Beaver Habitat, N. Minnesota (Naiman *et al.*, 1991)			
- permanently wetted	-	11-15	May-October
- seasonally inundated forest and meadow	-	0.3-0.5	1988
Boreal, Alberta (Vitt *et al.*, 1990)			
- beaver pond	518	76.2	May-October
- boreal marsh	148	21.7	1989
- rich fens	24 to 65	3.4-9.5	
- poor fen	lower	0.1	
- bog	nd	-	
Subarctic, Quebec			
- fen	-	1.3 to 9.8	
Temperate, Quebec (Moore and Knowles, 1990)			
- swamp	-	1.2 to 4.2	April-November
- bog	-	0.1	1987-1988
Swamp, Virginia (Wilson *et al.*, 1989)			
- continually flooded	-	43.7 ± 7.8	**April-May**
- variable flooding	-	41.4 ± 20.5	**1985-1986**

TABLE 1 continued

	Daily Emission (mg m-2 day-1)	Annual Emission (g m-2 yr-1)	Duration of Study
Peatlands, N. Minnesota (Crill *et al.*, 1988)			
- forested bog	77 ± 21	11.6 [a]	May, June, August 1986
- fen	142 ± 19	21.3 [a]	
- open bog	294 ± 30	44.1 [a]	
- ponded fen	325 ± 31	48.8 [a]	
- dry bog	102 ± 13	15.3 [a]	
Beaver Habitat, Quebec (Ford and Naiman, 1988)			
- river and creeks	-	0.1-0.4	May-October 1984
- pond	-	5.9	
Arctic Tundra, Alaska (Whalen and Reeburgh, 1988)			
- eriophorum tussocks	-	8.0 ± 2.5	-
- carex stands	-	4.9 ± 0.7	
- moss sites	-	0.5 ± 0.2	
- intertussock areas	-	0.6 ± 0.3	
Alaska (Sebacher *et al.*, 1986)			
- moist tundra	4.9	0.7 [a]	August 1984
- waterlogged tundra	119	17.9 [a]	
- wet tussock meadow	40	6.0 [a]	
- alpine fen	289	43.4 [a]	
- boreal marsh	106	15.9 [a]	
Peatlands, N. Minnesota (Haris *et al.*, 1985)			
- bog	47-194	7.1-29.1 [a]	daylight hours August 1983
- fen	4	0.6 [a]	
- fen and bog	419	62.9 [a]	
- meadow	664	99.6 [a]	
- marsh	493	74.0 [a]	
- shoreline fen	165	24.8 [a]	
Arctic Tundra, Sweden (Svensson and Rosewall, 1984)			
- dry, poor ombotrophic	0.2	.04 [a]	June-September 1974
- flooded, minerotrophic	720	108 [a]	

[a] = assuming a 150 day growing season

TABLE 2

THE WETLAND METHANE EMISSION FACTORS SELECTED FOR USE IN PREVIOUS METHANE INVENTORIES

	Daily Emission (mg m^{-2} day^{-1})	Annual Emission (g m^{-2} yr^{-1})	Duration of Study
Emission Rates Selected (Jaques, 1991)			
- forested and non-forested bogs	150	22.5	assuming growing season of 150 days for latitudes between 30° N and 60° N
- forested swamps	50	7.5	
- non-forested swamps	90	13.5	
- alluvial formations	20	3.0	
Emission Rates Selected (Matthews and Fung, 1988)			
- forested and non-forested bogs	200	30	assuming growing season of 150 days for latitudes between 30° N and 60° N and
- forested swamps	70	10.5	
- non-forested swamps	120	18	
- alluvial formations	30	4.5	

are not flooded or saturated at the surface for significant periods when organic matter is decomposing, the conditions required for methane generation. The methane-emitting wetland area is considered to be the portion of the total wetland that is organic soils, plus 10% of the gleysol cover (10% is an estimate of the proportion of gleysols ponded for significant periods during the growing season). The relative proportions of organic soils and gleysols is determined from the available soil mapping. Where mapping was not available the proportions were estimated from the data for similar regions (Table 3).

The proportion of different wetland types in each physiographic region, was estimated by Charles Tarnocai of the Land Resource Research Center, Agriculture Canada and Allen Banner, Regional Ecologist for the Prince Rupert Forest Region. These data, along with the calculated annual methane emission are shown in Table 4.

Annual methane emission from B.C. wetlands is estimated to be 1.3 x 10^8 kg yr^{-1}. Given the scarcity of extensive field measurements, the total lack of data from B.C., and the uncertainty regarding the areas of different wetland types, the associated error is estimated to be very high, possibly in excess of 100%.

Many of the methane emission research projects are ongoing (for example, that carried out by Dr. Vitt at the University of Alberta) and future results will likely change the emission projections. Given the many unique environmental factors in this province, and the complexity of wetland ecology, more reliable estimates of methane emission will require specific study of B.C. wetlands.

MARINE ENVIRONMENTS

Many studies have shown high rates of methane production from organic-C and CO_2 in marine sediments (Martens and Berner, 1974; Kuivila *et al.*, 1990). In seawater, methanogenesis is thermodynamically and kinetically suppressed by sulphate reduction (Rudd and Taylor, 1980; Devol, 1983). Consequently, methane production only occurs in deeper sediment layers where the interstitial sulphate concentration is low. Methane diffusing upwards is anaerobically oxidized at the base of the sulphate reduction zone, before entering the water column.

According to Dr. Devol at the University of Washington (personal communication), even in the most anaerobic inlet (Saanich Inlet), surface methane emission is negligible. The only marine situation in which Dr. Devol was aware of significant surface methane emission was from the degassing events occurring from the dewatering of sediments along the subduction zone. The bubbles of methane produced by this process are sufficiently buoyant to avoid anaerobic sulphate oxidation and the aerobic oxidative processes nearer the surface.

LAKES AND RIVERS

Annual Emission Rates

Methane production occurs in the anaerobic sediments of freshwater lakes and rivers where organic matter is being decomposed. Production rates are determined primarily by organic matter availability and by temperature (Kelly and Chynoweth, 1981). Methane loss to the atmosphere occurs from

1. the flooding of soils creates anaerobic conditions necessary for methanogenic bacteria;

2. the creation of shallow ponds with large surface areas for absorption of solar radiation which result in greater thermal inertia than in forest soils, maintaining high temperatures that facilitate methanogenesis;

3. the increase in habitat for emergent aquatic plants, which transfer large quantities of methane directly from sediments to the atmosphere and circumvent oxidation in the water column; and

4. the great quantities of carbon that are accumulated by beaver ponds (Naiman *et al.*, 1990).

The discrepancy between the beaver pond emission rate of 76 g $m^{-2} yr^{-1}$ measured by Vitt *et al.* (1990) and 11 to 15 g $m^{-2} yr^{-1}$ measured by Naiman *et al.* (1991) may be attributable to many factors (for example, pond size and depth). Dr. Moore of McGill University (personal communication) indicated that the high beaver pond emission rate measured by Vitt *et al.* (1990) is likely an artifact of mud disturbance during the study.

The annual emission rates selected for use in this project were based on the research of Moore and Knowles (1990), Vitt *et al.* (1990), and Naiman *et al.* (1991). They are the following:

beaver ponds	15 g $m^{-2} yr^{-1}$
marshs	20 g $m^{-2} yr^{-1}$
fens and swamps	5 g $m^{-2} yr^{-1}$
bogs	0.5 g $m^{-2} yr^{-1}$

Wetland Inventory Data

Terrain and vegetation surveys and inventories providing information on the extent of wetlands in British Columbia are listed in Appendix 4.

The data used for this project are contained in Van Ryswyk *et al.* "Distribution and Agricultural Use of Wetlands in British Columbia". A draft copy of this report, which is still undergoing revisions, was provided by the senior author. The report provides estimates of wetland areas and, where possible, that of organic and mineral wetland soils (Table 2), compiled from existing soil surveys and published and unpublished CLI mapping. The area of wetland indicated by the marsh designation on NTS maps was used for areas of the province not covered by CLI or soil maps.

A subsequent inventory of peatland by Maynard (1988) covering approximately 70% of the province, includes data from more recently published surficial geology, terrain and soil maps. However it only maps wetlands where the peat depth is greater than 40 cm. The study ended at the mapping stage and requires digitizing to calculate peatland areas.

The definition of wetland soils used by Van Ryswyk *et al.* (unpublished) includes gleysols, soils that have properties indicating prolonged periods of saturation within 50 cm of the surface. Many gleysols

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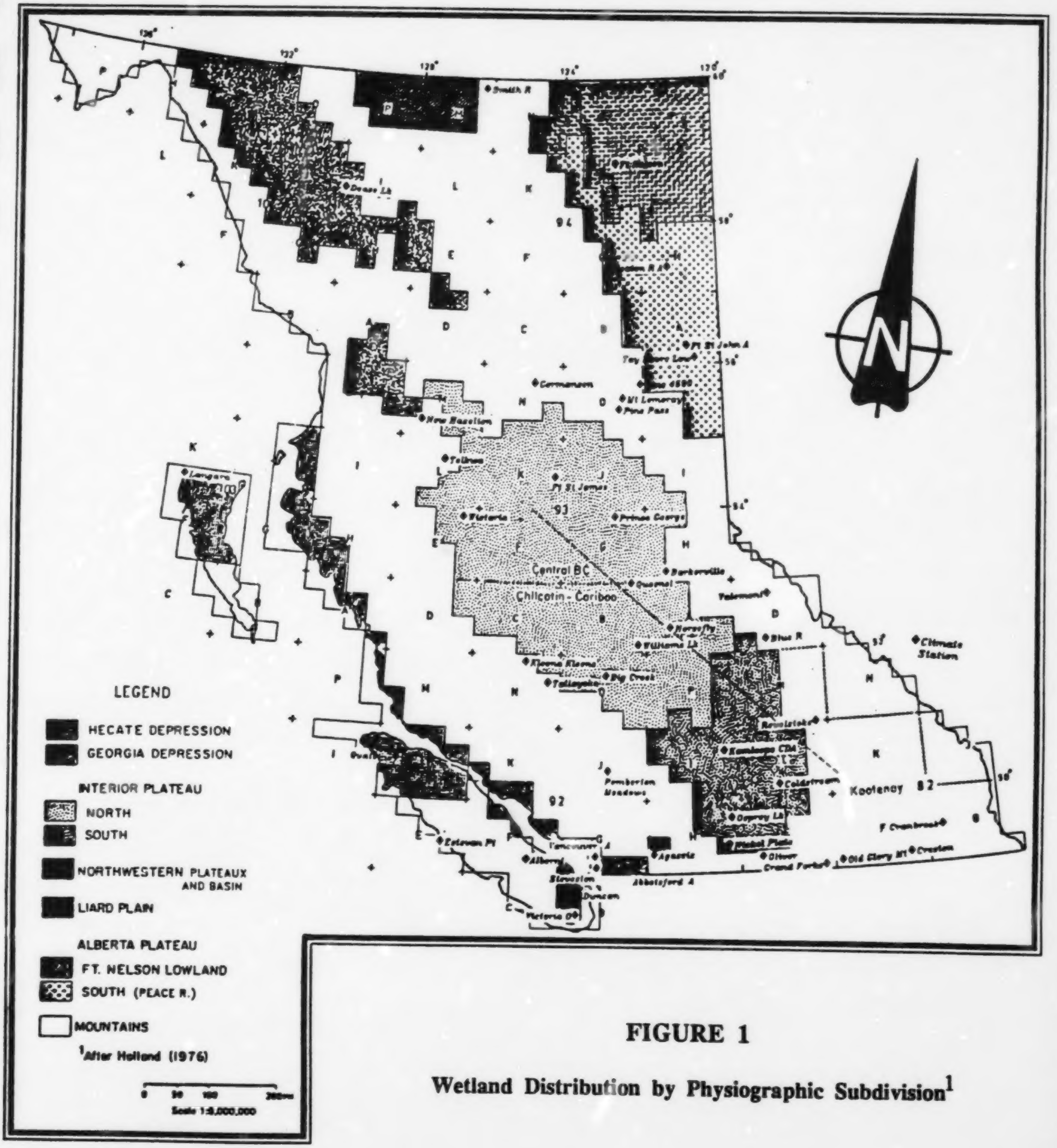

FIGURE 1

Wetland Distribution by Physiographic Subdivision[1]

TABLE 3

THE AREA OF WETLANDS IN DIFFERENT PHYSIOGRAPHIC REGIONS OF B.C.

Physiographic Region [*a]	Wetland Region [*b]	Total Area [*a] (km^2)	Total Wetland (km^2)	Where Surveyed		Total CH$_4$-Emitting Wetland (km^2)
				% Organic	% Gleysol	
Hecate Depression	Pacific Oceanic	31,278	1,912	70[*c]	30[*c]	1,395
Georgia Depression	Temperate Pacific	12,095	721	30	70	267
Southern Plateau	Intermountain Prairie	51,329	972	39	61	438
Chilcotin/Caribou Plateau	Intermountain Prairie/ Mid Boreal	63,877	2,589	71	29	1,913
Central Plateau	Mid Boreal	87,839	3,486	64	36	2,356
Northwestern Plateau	Mid/High Boreal	68,725	841	65[*c]	35[*c]	576
Liard Plain	High Boreal	15,712	762	65[*c]	35[*c]	522
Alberta Plateau:						
Fort Nelson Lowland	High Boreal/Low Subarctic	50,290	23,852	89	11	21,491
Peace River Lowland	Mid-Boreal	52,450	9,582	43	57	4,666
Mountain	Mountain	513,410	4,127	8	92	710
						32,334

[*a] the physiographic subdivision is shown in Figure 1, adapted from Van Ryswyk *et al.* (unpublished)

[*b] according to National Wetlands Working Group, 1988

[*c] estimated

TABLE 4

ANNUAL METHANE EMISSION FROM WETLANDS IN B.C.

	ALL CH_4-EMITTING WETLANDS					ANNUAL CH_4 WETLAND EMISSIONS				
PHYSIOGRAPHIC REGION	**Beaver Ponds**	**Marshes**	**Fens & Swamps**	**Bogs**	**Total**	**Beaver Ponds @15**	**Marshes @20**	**Fens & Swamps @5**	**Bogs @0.5**	**Total**
	%	%	%	%	km^2	10^3 kg/yr using above emission rates in g/m^2yr				
Hecate Depression	2	2	10	86	1,395	419	558	698	600	2,275
Georgia Depression	2	2	40	56	267	80	107	534	75	796
Southern Plateau	4	76	20	-	438	263	6658	438	-	7,359
Chilcotin-Caribou	4	56	40	-	1,913	1,148	21,426	3,826	-	26,400
Central Plateau	4	20	66	10	2,356	1,414	9,424	7,775	118	18,731
Northwestern Plateau	4	5	56	35	576	346	576	1,613	101	2,636
Liard Plain	4	2	54	40	522	313	209	1,409	104	2,035
Fort Nelson Lowland	2	2	30	64	21,491	6,447	8,596	32,236	6,877	54,156
Peace River Lowland	2	2	34	60	4,666	1,400	1,866	7,932	1,400	12,598
Mountains	2	10	31	55	710	213	1,420	1,100	195	2,928
Totals					**34,334**	**12,043**	**50,840**	**57,561**	**9,470**	**129,914**

emitted bubbles, from diffusion through the porous stems of aquatic plants (Dacey and Klug, 1979), or through limited surface exchange when lakes turnover, primarily in the fall (Rudd and Taylor, 1980). Most of the research to date has focused on the role of methanogenesis and methane oxidation in carbon cycling (Rudd and Hamilton, 1978; Kelly and Chynoweth, 1981; Lilley *et al.*, 1988). The only published measurements of annual methane emission from northern lakes found by the current study were the data from beaver ponds (Ford and Naiman, 1987; Naiman *et al.*, 1991; Vitt *et al.*, 1990).

Consequently, the study estimates of freshwater methane emission are based on yet unpublished results from studies of shallow lakes in the Hudson Bay Lowland and deeper oligotrophic lakes in the Experimental Lakes area near Kenora (Dr. John Rudd, personal communication). According to Dr. Rudd, emission from shallow lakes averages 100 to 300 mg m^{-2} d^{-1} (15 to 45 g m^{-2} yr^{-1}). Methane emission to the atmosphere is 2 to 4 orders of magnitude lower from the deeper lakes. Even in the eutrophic deep lakes that turnover, Dr. Rudd stated that little methane escapes from the hyperlimnion (<1 g m^{-2} yr^{-1}).

Freshwater Inventory Data

Boyd (1983), quoting Farley (1979), stated that the area of freshwater lakes in B.C. is 2×10^6 ha. The B.C. Environment and Land Use Secretariat (1976) reports that the area of fresh water surfaces in B.C. total 2.3×10^6 ha. Assuming that 25% of this surface is on shallow lakes emitting 30 g m^{-2} yr^{-1}, the methane emission from this source is 1.7×10^4 kg yr^{-1}. Given the lack of information on methane emission and areas for the different lake types, the error associated with this estimate is high, probably in excess of 200%. The emission estimate should be modified as future data becomes available.

3.0
METHANE UPTAKE BY AEROBIC SOILS

Recent studies have shown that aerobic soils are capable of consuming significant rates of methane (Table 3). However aerobic soils generally contain both aerobic methane - consuming and anaerobic methane-producing microsites. It is the balance between production and consumption that determines whether an aerobic soil is a source or sink of atmospheric methane. Studies show that the organic-rich surface and wetter subsoil layers of aerobic soils can be net sources of methane emission (Sexstone and Mains, 1989; Yavitt *et al.*, 1990).

Yavitt *et al.* (1990) found that the entire profile of the wetter of the two aerobic Appalachian forest soils they sampled was producing methane. Steudler *et al.*, who measured a high methane consumption rate in a New England forest soil, found that methane uptake rates were decreased by increases in soil moisture and by nitrogen additions.

TABLE 5

A SUMMARY OF THE MEASUREMENTS OF METHANE UPTAKE BY AEROBIC SOILS

SOIL TYPE	METHANE CONSUMPTION mg m^{-2} d^{-1}	SOURCE
temperate forest soils	0.2	Keller *et al.*, 1983
	4.2	Steudler *et al.*, 1989
	0.6	Yavitt *et al.*, 1990
tundra soils	0.6-1.2	King *et al.*, 1989

An additional unknown factor confounding the issue of methane consumption by aerobic soils is the role of soil fauna. According to Zimmerman *et al.* (1982), methane is generated in the guts of xylophagous (wood eating) insects. The best known example is termites. Measurements carried out in the tropics show that termites produce huge quantities of methane (Zimmerman *et al.*, 1982; Rasmussen and Khalil, 1983).

Various authors consider aerobic soils as a small but significant sink in the global methane budget (Bouwman, 1989; Steudler *et al.* 1989; Nisbitt, unpublished). The category of aerobic soils covers a great variety of soil types, with a wide range of properties that will obviously cause considerable differences in the methane flux (for example, humid coastal podzols compared to soils in drier regions). Compared to soils in most of the world, B.C. soils are cooler, and have more surface litter, properties that are likely to reduce methane uptake.

The area of aerobic soils in B.C. is approximately 900,000 km^2 (Van Ryswyk *et al.*, unpublished). Assuming that this cover consumes methane at an average rate of 0.6 mg m^{-2} d^{-1} for half the growing season (75 days), the net uptake for B.C. would be 4.1 x 10^7 kg yr^{-1} (0.045 g m^{-2} yr). Given the tentative exploratory nature of the published research, the error associated with this estimate is high, probably in excess of 200%. Research projects in Alaska and Central Canada are presently looking at methane uptake on a range of soils, and extrapolation from these data should be used to improve this estimate. Given the unique qualities of many B.C. soils, there is certainly a need to carry out research of this type in this province.

4.0
FUTURE CHANGES

Future methane emissions from the natural terrain in southern heavily populated portions of the province can be expected to decrease as urban areas drain the adjacent wetlands. Future agricultural expansion, although smaller in scope, is likely to have a similar effect.

Increases in methane emission will result from any hydroelectric projects which flood carbon stores in peat, forest floors and vegetation. Logging will increase methane emission through increased termite consumption of felled timber, and from the greater litterfall and beaver activity associated with deciduous regeneration in second growth stands. In the period 1930-1950 beaver numbers were extremely low in Canada, as a result of trapping and disease. Since 1950, conservation, coupled with low prices for beaver pelts, the deciduous second growth in many areas after logging, and the removal by man of predators, have allowed beaver to reach very high numbers (Nesbit, 1989a). Conservation measures could include increasing the numbers of predators like wolf and lynx to reduce the number of beaver, or forest policies to reduce the extent of deciduous second growth.

One of the largest potential sources of CH_4 emission is natural gas hydrates. These occur worldwide in marine sediments under the necessary combination of temperature and pressure. Hydrates also occur in permafrost. Estimated methane quantities in permafrost are 3×10^{13} - 6×10^{13} m^3, with roughly 10^{16} m^3 in shelf and continental shelf reservoirs. Sediment and permafrost hydrate methane will be released with temperature and sea level increases associated with global warming. While methane in marine sediments is likely to be oxidized prior to reaching the surface, the hydrated methane in permafrost will probably be released to the atmosphere. Significant areas of permafrost occurring in the northeast corner of British Columbia (Valentine *et al.*, 1978) would be effected. However, emissions from B.C. are likely to be only a small fraction of the amount emitted from the much larger areas of permafrost further north.

The effect of global warming on wetland methane emission will depend to a large degree on water table positions. If the wetlands remain wet, with water tables at or above the surface, then increased temperatures should increase emission rates. If the wetlands become drier, emission rates may be expected to decrease, with concurrent increases in methane uptake.

APPENDIX 1

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APPENDIX 2

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APPENDIX 3

CLASSIFICATION OF WETLAND TYPES
(from National Wetlands Working Group, 1988)

There are five wetland classes in the Canadian classification system: **bog, fen, swamp, marsh, and shallow open water**. There are terms familiar to the layman and wetland ecologist alike. It is not surprising, therefore, that a close examination shows that there are many subtly or substantially different definitions of these terms. One solution is to abandon them completely, as is done by Cowardin *et al.* (1979), just as the term "muskeg" has been abandoned because of conflicting definitions. The other solution is to define them, keeping in mind the possibility of other usage but putting them into a Canadian context. The resulting definitions would then be applicable to the wetland classes found in Canada, from cool temperate to polar regions, and from perhumid oceanic to semi-arid continental climatic conditions.

Wetlands are not synonymous with peatlands. Peatlands are those wetlands which have a peat layer of 40 cm or more in thickness (Tarnocai 1980). This limit was chosen because at this thickness the bast majority of wetland plants are rooted in peat.

BOGS are peat-covered wetlands in which the vegetation shows the effects of a high water table and a general lack of nutrients. The bog surface is often raised, but if it is flat or level with the surrounding wetlands, it is virtually isolated from mineralized soil waters. Hence the surface waters of bogs are strongly acid and the upper peat layers are extremely deficient in nutrients. Peat is usually formed *in situ* under closed drainage and oxygen saturation is low. The thickness of peat exceeds 40 cm. Cushion-forming *Sphagnum* mosses are common, along with heath shrubs. Trees may be absent; if present, they form open-canopied forests of low, stunted trees.

This definition of bogs is intended to correspond to extremely nutrient-poor ("ombrotrophic" or oligotrophic") wetlands where the living vegetation is not nourished by mineral-enriched ("minerotrophic") groundwater. The pH value of the groundwater is generally less than 4.6 with conductivity values below 80 *u*S/cm. These low conductivity values reflect the low calcium (Ca) and magnesium (Mg) values in the water: the combined value of these elements is less than 5 mg/L. The low nutrient levels are also reflected in the total mineral content of the peat within the rooting zone. The pH value of the peat is less than 4.7 and the combined Ca and Mg content is generally less than 5 000 mg/kg.

FENS are peatlands characterized by a high water table, but with a very slow internal drainage by seepage down very low gradient slopes. The oxygen (O) saturation is relatively low but higher than in bogs. A slowly moving water table is enriched by nutrients from upslope materials and thus fens are more minerotrophic than bogs. The thickness of peat generally exceeds 40 cm. The vegetation in fens usually reflects the water quality and quantity available, resulting in three basic types: graminoid fens without trees or shrubs, shrub fens, and treed fens.

The nutrient content of fen waters and fen peat is always higher than that of bogs in the same area. However, analyses show that some "rich fens" may be highly mineral-rich ("eutrophic") with alkaline reaction and very high Ca and Mg values. Under certain circumstances, however, other fens are almost as poor in nutrients as bogs (and are considered "poor fens"). Such circumstances occur where the groundwater is derived from mineral-poor areas, such as the Swan Hills of Alberta (Vitt *et al.* 1975), and where the water originates in domed bogs (Glaser *et al.* 1981). However, most fens have moderate levels of nutrients and are considered "mesotrophic" with slightly acid (pH 5.5-6.0) reaction.

SWAMPS are wetlands where standing or gently moving waters occur seasonally or persist for long periods, leaving the subsurface continuously waterlogged. The water may also be present as a subsurface flow of mineralized water. the water table may drop seasonally below the rooting zone of vegetation, creating aerated conditions at the surface. Swamp waters are circumneutral to moderately acid in reaction, and show little deficiency in oxygen or mineral nutrients. Their substrate consists of mixtures of mineral and organic materials, or woody, well-decomposed peat deposited *in situ*. The vegetation may consist of dense coniferous or deciduous forest, or tall shrub thickets.

Swamps are usually nutrient-rich, productive sites where trees and shrubs show luxuriant growth. Generally, the nutrient levels are high both in the groundwater and in the peat. Most peat-forming mosses are absent, or present only in a subordinate role. The peat being deposited in swamps is usually woody and highly humified and in many swamps, peat formation in minimal. In some cases, swamps develop on the surface of other peatlands, such as fens or bogs, as shown by the sequence of peat deposition.

MARSHES are wetlands that are periodically inundated by standing or slowly moving water and hence are rich in nutrients. Marshes are mainly wet, mineral-soil areas, but shallow, well-decomposed peat may be present. Marshes are subject to a gravitational water table, but water remains within the rooting zone of plants for most of the growing season. Waters are usually circumneutral to slightly alkaline, and there is a relatively high oxygen saturation. They are characterized by an emergent vegetation of reeds, rushes, or sedges.

The surface water levels of marshes may fluctuate seasonally (or even daily due to tides in coastal situations), with declining levels exposing draw-down zones of matted vegetation or mudflats. The vegetation shows a distinct zonation according to water depth, frequency of drawdowns, or salinity.

SHALLOW OPEN WATERS, locally known as ponds or sloughs, are relatively small, non-fluvial bodies of standing water representing a transitional stage between lakes and marshes. The surface waters impart an open aspect, free of emergent vegetation, but floating, rooted, aquatic macrophytes may be present. The depth of water is usually less than 2 m at midsummer levels.

APPENDIX 4

DATA SOURCES SHOWING THE AREA OF WETLANDS IN B.C.

Wetland Distribution in Canada in
Canada's Wetlands
National Wetlands Working Group (1986)
Energy Mines and Resources Canada and Environment Canada
Ottawa, Ontario

- 1:7x10^6 scale map, showing the percent cover of wetlands (0-5%, 6-25%, 26-50%, 51-75% and 76-100%);

- data was derived from the CLI, forest cover maps and from information provided by individual resource managers.

Soils of British Columbia
H.A. Luttmerding, Senior Soils Specialist
Integrated Management Branch
B.C. Ministry of the Environment

- manuscript copy of 1:10^6 scale soils map for the southern half of B.C., the northern half is in progress;

- for each polygon there is information on the drainage, classification, parent material, extent, and other properties of the dominant and subdominant soil types and any minor included soils;

- data was obtained from a variety of sources including soil surveys (where available), terrain mapping and the CLI.

Forest Cover Maps
B.C. Ministry of Forests
c/o Anthony Britneff, Inventory Branch
Victoria

- 1:50,000 scale maps including the area of water and of non-forested bogs, and the areas of species, such as larch and black spruce, associated with wetland terrain;

- the computerized data in expanded grid area file can retrieved from Ministry of Forests tapes.

D.E. Maynard, 1988
Peatland Inventory of British Columbia
Mineral Resources Division
Geological Survey Branch

- 1:250,000 mapping of peatlands for over half the province. Peatlands are defined, as per the Canadian soils classification, as wetlands in which organic accumulations are at least 40 cm thick;
- the data was derived primarily from existing soils, terrain and surficial geology mapping, but also includes peatland mapping of the Pacific coast by Tarnocai (in preparation) and, where no other information was available, the CLI;
- approximately 30% of the province was not mapped due to insufficient data;
- where possible the mapping distinguishes between different peatland types (bogs of various types, fens of various types, and undifferentiated);
- the data exists only on the maps. According to Dan Hora, the project co-ordinator, no effort has been made to determine the areas of different peatland types.

Al Van Ryswyk, J.A. Hall and K. Broersma (in preparation)
Distribution and Agricultural Use of Wetlands in British Columbia
Agriculture Canada

- a not yet published report giving the areal extent of wetlands for the entire province;
- derived from soil maps, the Canada Land Inventory Soil Capability for Agriculture (CLI) and 1:50,000 National Topographic Survey maps. For each, it lists the area of wetlands, and where known the area of organic and gleysolic soils; (1:50,000 map sheet and physiographic region);
- notably this source did not use several recently published surveys included by Maynard (1988).

APPENDIX IV

DETAILED METHANE EMISSIONS INVENTORY

EMISSIONS FROM COMBUSTION SOURCES

Major Sectors		Fuel Type	EMPR 1990 Fuel Req. (PJ)	EMPR 1989 Fuel Req. Actual	EMPR 2005 Fuel Req. Forecast	Emis.Fact. t/PJ	tonnes CH4 1990	tonnes CH4 2005	Ref.& Notes
COMBUSTION SOURCES:									
Fossil Fuel Elec.Prod.									
	Gas Utilities	NGAS	13.03	44.04	40.26	0.13	1.68	5.19	
		DFO	1.59	1.02	1.53	0.17	0.27	0.26	
Total Gas Utilities			14.62	45.06	41.79		1.95	5.46	
	Power Generation	NGAS	3.68	3.62	5.98	1.30	4.78	7.77	Adhoc
		DFO	0.98	1.53	1.50	12.50	12.25	18.75	Adhoc
		HFO	3.11	3.12	4.20	0.82	2.55	3.44	Adhoc
		PULP LIQ.	6.15	6.12	6.79	0.00	0.00	0.00	
		HOG	3.34	3.31	13.57	4.70	15.70	63.78	
Total Power Generation			17.26	17.70	32.04		35.28	93.75	
Residential									
	Heating/Cooking	DFO	3.41	3.28	3.83	8.30	28.30	31.79	Adhoc
		LFO	11.41	11.55	3.42	5.50	62.76	18.81	Adhoc
		LPG	1.31	1.33	0.55	1.10	1.44	0.61	Adhoc
		NGAS	81.35	78.34	119.34	1.15	93.55	137.24	Adhoc
Total Residential			97.48	94.50	127.14		186.05	188.45	
Commercial									
	Proc.Heat/Energy	DFO	4.93	5.16	4.33	12.50	61.63	54.13	Adhoc
		HFO	1.17	1.25	0.84	1.37	1.60	1.15	Adhoc
		LFO	4.97	5.01	3.12	0.67	3.33	2.09	Adhoc
		LPG	2.53	2.56	1.61	1.10	2.78	1.77	Adhoc
		NGAS	35.84	33.22	56.65	1.15	41.22	65.15	Adhoc
Total Commercial			49.44	47.20	66.55		110.56	124.28	

EMISSIONS FROM COMBUSTION SOURCES

Major Sectors	Fuel Type	EMPR 1990 Fuel Req. (PJ)	EMPR 1989 Fuel Req. Actual	EMPR 2005 Fuel Req. Forecast	Emis.Fact. t/PJ	tonnes CH4 1990	tonnes CH4 2005	Ref.& Notes
COMBUSTION SOURCES:								
Industrial								
Pulp & Paper	NGAS	23.69	23.41	45.16	1.30	30.80	58.71	
	C&C	0.26	0.25	0.23	0.51	0.13	0.12	
	HFO	23.57	23.39	18.62	0.82	19.33	15.27	
	LPG	0.33	0.33	0.39	1.10	0.36	0.43	
	DFO	0.50	0.50	0.63	12.50	6.25	7.88	
	HOG	46.93	46.67	59.56	4.70	220.57	279.93	
	PULP LIQ.	133.01	132.42	141.68	0.00	0.00	0.00	
	OTHER	0.72	0.71	1.45	0.00	0.00	0.00	
Total Pulp & Paper		205.32	204.27	222.56		246.64	303.62	
Wood Prod.	NGAS	14.01	14.05	15.22	1.30	18.21	19.79	
	HFO	0.00	0.00	0.00	0.82	0.00	0.00	
	LFO	0.09	0.09	0.02	0.16	0.01	0.00	
	LPG	0.55	0.60	0.15	1.10	0.61	0.17	
	DFO	1.60	1.84	0.43	12.50	20.00	5.38	
	HOG	21.84	22.03	22.79	4.70	102.65	107.11	
Total Wood Products		38.09	38.61	38.61		141.48	132.44	
Primary Metals	NGAS	1.81	2.03	2.31	1.30	2.35	3.00	
	HFO	0.04	0.04	0.01	0.82	0.03	0.01	
	LFO	0.05	0.05	0.02	0.16	0.01	0.00	
	DFO	0.09	0.10	0.03	12.50	1.13	0.38	
	LPG	0.00	0.00	0.00	1.10	0.00	0.00	
Total Primary Metals		1.99	2.22	2.37		3.52	3.39	
Chem. Ind.	NGAS	4.54	4.55	4.53	1.30	5.90	5.89	
	HFO	0.66	0.64	0.45	0.82	0.54	0.37	

EMISSIONS FROM COMBUSTION SOURCES

Major Sectors	Fuel Type	EMPR 1990 Fuel Req. (PJ)	EMPR 1989 Fuel Req. Actual	EMPR 2005 Fuel Req. Forecast	Emis.Fact. t/PJ	tonnes CH4 1990	tonnes CH4 2005	Ref.& Notes
COMBUSTION SOURCES:								
	LFO	0.04	0.04	0.03	0.16	0.01	0.00	
	DFO	0.00	0.00	0.00	12.50	0.00	0.00	
Total Chemical Industries		5.24	5.23	5.01		6.45	6.26	
Non-Metallic	NGAS	2.83	2.71	3.37	1.30	3.68	4.38	
	C&C	0.98	0.94	1.15	0.51	0.50	0.59	
	DFO	0.10	0.09	0.11	12.50	1.25	1.38	
	LPG	0.01	0.01	0.01	1.10	0.01	0.01	
	PCOKE	0.74	0.71	0.81	0.38	0.28	0.31	
	OTHER	0.16	0.16	0.19	0.00	0.00	0.00	
Total Non-Metallic		4.82	4.62	5.64		5.72	6.66	
Petroleum Ref.	DFO	0.47	0.47	0.39	12.50	5.88	4.88	
	HFO	0.42	0.34	0.39	0.82	0.34	0.32	
	LFO	0.01	0.02	0.01	0.16	0.00	0.00	
	MOTOR GAS	0.16	0.22	0.11	0.17	0.03	0.02	
	PETR.COKE	1.86	1.98	1.89	0.38	0.71	0.72	
	STILL GAS	17.28	17.25	11.84	1.30	22.46	15.39	
	NGAS	9.91	9.74	5.73	1.30	12.89	7.45	
Total Petroleum Ref.		30.11	30.02	20.36		42.31	28.77	
Mining	NGAS	6.05	5.41	7.82	1.30	7.87	10.17	
	C&C	0.00	0.00	0.00	0.51	0.00	0.00	
	LFO	0.00	0.00	0.00	0.16	0.00	0.00	
	DFO	7.12	7.55	5.02	12.50	89.00	62.75	
	LPG	0.26	0.28	0.19	1.10	0.29	0.21	

EMISSIONS FROM COMBUSTION SOURCES

Major Sectors	Fuel Type	EMPR 1990 Fuel Req. (PJ)	EMPR 1989 Fuel Req. Actual	EMPR 2005 Fuel Req. Forecast	Emis.Fact. t/PJ	tonnes CH4 1990	tonnes CH4 2005	Ref.& Notes
COMBUSTION SOURCES:								
Total Mining		13.43	13.24	13.03		97.15	73.13	
Other Mfg.	**NGAS**	18.17	16.61	29.37	1.30	23.62	38.18	
	C&C	0.00	0.00	0.00	0.51	0.00	0.00	
	HFO	0.17	0.17	0.10	0.82	0.14	0.08	
	LFO	0.24	0.24	0.19	0.16	0.04	0.03	
	DFO	0.74	0.74	1.17	12.50	9.25	14.63	
	LPG	0.28	0.28	0.44	1.10	0.31	0.48	
Total Other Mfg.		19.60	18.04	31.27		33.36	53.40	
Other Ind.	**NGAS**	5.50	5.42	6.88	1.30	7.15	8.94	
	LFO	1.37	1.37	1.37	0.16	0.22	0.22	
	DFO	12.13	12.13	12.13	12.50	151.63	151.63	
	HFO	0.10	0.10	0.10	0.82	0.08	0.08	
Total Other Industries		19.10	19.02	20.48		159.08	160.87	
TOTAL INDUSTRIAL		338	335	359		736	769	
TOTAL COMBUSTION SOURCES:		516	540	627		1,070	1,180	

EMISSIONS FROM MOBILE SOURCES

MOBILE SOURCES:		EMPR 1990 Fuel Req. (PJ)	EMPR 1989 Fuel Req. Actual	EMPR 2005 Fuel Req. Forecast	Emis.Fact. t/PJ	tonnes CH4 1990	tonnes CH4 2005	Ref.& Notes
Road (Gasoline)	LDGV	89.3		94.6	47.7	4259	2838	
	LDGT1	47.6		50.5	47.7	2272	1514	
	LDGT2	1.8		1.9	47.7	84	56	
	HDGV	0.5		0.5	47.7	23	15	
	MC	0.1		0.1	47.7	6	4	
Total Road Gasoline		139.3		147.6		6,645	4,428	
Road (Diesel)	LDDV	1.0		1.4	4.4	5	6	
	LDDT	1.1		1.5	4.4	5	7	
	HDDT	63.1		84.0	4.4	275	389	
Total Road Diesel		65.3		86.9		285	402	
Aircraft	Av.Gas	1.3	1.3	1.8	11.7	15	21	Adhoc
	Av.Turbo	33.4	33.4	45.4	11.5	384	522	Adhoc
Total Aircraft		34.7	34.6	47.1		399	542	
Marine	HFO	17.1	16.7	21.4	40.0	684	856	Adhoc
	DFO	13.8	13.7	17.8	45.0	620	800	Adhoc
Total Marine		30.9	30.4	39.2		1304	1656	
Railroads	DFO	13.1	12.9	13.7	7.8	102	107	Adhoc
Off-Road	Gasoline	5.4	5.4	5.4	47.7	257	257	
TOTAL MOBILE SOURCES:		289		340		8,991	7,393	

Incineration	1990	2005	Units	Emission factor	Units	tonnes CH4 1990.00	tonnes CH4 2005.00	
Woodwaste	87	87	PJ	77	tonnes/PJ	6,699	6,699	BHLA
Fraser River Debris	12,000	10,000	tonnes	3.5	g/Kg	42	35	MOF
MSW	239,752	239,752	tonnes	0.23	g/Kg	54	54	CEC
TOTAL INCINERATION						6,795	6,788	

SECTOR	Throughput (kt) 1990	2005	THC Emission	CH4 Content	tonnes CH4 1990	tonnes CH4 2005
Natural Gas						
Production	11,203	19,683	0.39%	71.5%	31,240	54,886
Processing	11,203	19,683	0.11%	71.5%	8,811	15,481
Transmission	7,880	13,876	0.03%	91.1%	2,154	3,792
Distribution	4,500	7,928	0.03%	NA	1,350	2,378
Total Natural Gas	34,786	61,170			43,554	76,537
Oil						
Production	1,666	672	1.43%	71.5%	17,034	6,871
Transportation						
Crude Oil	5,585	8,961	0.05%	5.0%	140	224
HVP	350	615	0.04%	5.0%	7	12
LVP	210	369	0.07%	5.0%	7	13
Total Oil	7,811	10,617			17,188	7,120

Estimate of methane emissions from landfills in British Columbia
For the period of 1990 & 2005 (tonnes/yr)

City	Landfill Name	1990	2005
Vancouver	Portmann	12,290	5,692
Vancouver	Burns Bog	65,300	51,590
Victoria	Hartland1	43,540	15,650
Victoria	Hartland2	0	21,460
Cache Creek		1,435	8,454
Matsqui	Valley Rd.	1,260	1,255
N.Vancouver	Premier St.	4,762	3,129
Richmond		13,270	8,720
Coquitlam	Braid St.	9,272	6,093
Prince Rupert	Wantage Rd.	1,369	930
Prince Rupert	Wainright	0	788
Kamloops	Mission	1,430	2,460
Kamloops	Guerin Creek	1,210	1,042
Kamloops	Banhart	227	349
	Others	73,260	67,200
Total MSW		228,625	194,811
Woodwaste		49,320	69,550
Pulpwaste		12,460	18,530
TOTAL LANDFILL EMISSIONS		290,405	282,891

	Coal mined tonnes 1990	Coal mined tonnes 2005	Emission factor kg CH4/t mined	tonnes CH4 1990.00	tonnes CH4 2005.00	
TOTAL COAL MINES	25,800,000	25,400,000	2.00	51,600	50,800	ENV.CAN.

Prescribed Fires

	1990 Hectares burnt		1990 tonnes CH4 Forest Mgmt.	1990 tonnes CH4 Range/ Wildlife	TOTAL 1990 EMISSIONS tonnes CH4	TOTAL 2005 EMISSIONS tonnes CH4	
Region	Forest Mgmt.	Range/ Wildlife					
Vancouver	3,165	0	886	0	886		
P.Rupert	6,375	2,020	1,785	141	1,926		
P.George	18,896	39,179	5,291	2,743	8,033		
Kamloops	13,326	26	3,731	2	3,733		
Nelson	2,976	2,461	833	172	1,006		
Cariboo	7,284	1,603	2,040	112	2,152		
TOTAL PRESC.BURNING	52,022	45,289	14,566	3,170	17,736	12,415	
Fuel Consumption (tonnes/ha)	80	20					
Average Emission factor (g/kg)	3.50	3.50					MOF

METHANE PRODUCTION FROM DOMESTIC LIVESTOCK AND POULTRY

ANIMAL CLASS	1990 ANIMAL NUMBERS	2005 ANIMAL NUMBERS	ANNUAL METHANE PRODUCTION KG/ANIMAL	1990 METHANE PRODUCTION TONNES/YEAR	2005 METHANE PRODUCTION TONNES/YEAR
DAIRY CATTLE					
Lactating	65,570	85,688	110.57	7,250	9,474
Dry	12,822	16,756	65.13	835	1,091
Replacements	28,000	36,591	67.44	1,888	2,468
Calves	28,000	36,591	32.28	904	1,181
BEEF CATTLE					
Brood Cows	228,000	250,800	50.33	11,475	12,623
Bulls	11,000	12,100	57.11	628	691
Replacements	42,000	46,200	46.68	1,961	2,157
Feedlot	33,354	36,690	22.29	743	818
Calves	200,000	220,000	42.96	8,591	9,450
SHEEP					
Ewes and Rams	25,400	25,400	7.82	199	199
Replacements	5,000	5,000	6.95	35	35
Market Lambs	4,500	4,500	3.70	17	17
GOATS					
Milking	10,000	10,000	16.31	163	163
Meat	10,000	10,000	9.19	92	92
Hobby	10,000	10,000	8.72	87	87
HOGS					
Sows	22,700	22,700	1.66	38	38
Boars	1,500	1,500	1.30	2	2
Market	340,176	340,176	0.85	288	288
POULTRY					
Lay Hens	2,407,652	2,407,652	0.02	41	41

Lay Pullets	2,407,652	2,407,652	0.00	7	7
Market Broilers	46,558,062	95,553,852	0.00	92	188
Market Roasters	2,244,938	4,391,782	0.00	10	19
Broiler Breeders	451,000	925,614	0.02	11	22
Breeder replacements	451,000	925,614	0.01	2	5
TURKEYS					
Light	819,000	1,400,215	0.01	5	8
Heavy	1,131,000	1,933,630	0.01	14	25
HORSES	75,000	75,000	16.55	1,241	1,241
TOTAL DOMESTIC LIVESTOCK & POULTRY				36,617	42,427

ESTIMATED METHANE PRODUCTION FROM MANURE FROM DOMESTIC LIVESTOCK AND POULTRY

ANIMAL CLASS	1990 ANIMAL NUMBERS	2005 ANIMAL NUMBERS	VOLATILE SOLIDS PRODUCTION KG/DAY	VOLATILE SOLIDS 1990 TONNES/YEAR	VOLATILE SOLIDS 2005 TONNES/YEAR	1990 CH4 PRODUCTION TONNES/YEA	2005 CH4 PRODUCTION TONNES/YEA
DAIRY CATTLE							
Lactating	65,570	85,688	6.0	143,598	187,657	26,732	34,934
Dry	12,822	16,756	6.0	28,080	36,696	5,227	6,831
Replacements	28,000	36,591	4.5	45,990	60,101	8,561	11,188
Calves	28,000	36,591	2.0	20,440	26,711	3,805	4,973
BEEF CATTLE							
Brood Cows	228,000	306,858	4.0	329,551	443,533	AEROBIC	AEROBIC
Bulls	11,000	14,800	5.8	23,126	31,116	AEROBIC	AEROBIC
Replacements	42,000	56,526	2.9	44,150	59,420	AEROBIC	AEROBIC
Feedlot	33,354	44,890	2.9	11,527	15,514	2,146	2,888
Calves	228,000	306,858	1.8	149,796	201,606	AEROBIC	AEROBIC
SHEEP							
Ewes and Rams	25,400	25,400	0.5	4,265	4,265	AEROBIC	AEROBIC
Replacements	5,000	5,000	0.3	504	504	AEROBIC	AEROBIC
Market Lambs	4,500	4,500	0.3	199	199	AEROBIC	AEROBIC
GOATS							
Milking	10,000	10,000	0.5	1,679	1,679	AEROBIC	AEROBIC
Meat	10,000	10,000	0.3	1,007	1,007	AEROBIC	AEROBIC
Hobby	10,000	10,000	0.5	1,679	1,679	AEROBIC	AEROBIC
HOGS							
Sows	22,700	22,700	1.4	11,620	11,620	2,163	2,163
Boars	1,500	1,500	1.7	931	931	173	173
Market	340,176	340,176	0.4	25,301	25,301	4,710	4,710
POULTRY							
Lay Hens	2,407,652	2,407,652	0.02	21,091	21,091	4,228	4,228

Lay Pullets	2,407,652	2,407,652	0.01	2,831	2,831	568	568
Market Broilers	46,558,062	95,553,852	0.02	36,408	74,723	AEROBIC	AEROBIC
Market Roasters	2,244,938	4,391,782	0.03	4,849	9,486	AEROBIC	AEROBIC
Broiler Breeders	451,000	925,614	0.04	6,469	13,277	AEROBIC	AEROBIC
Breeder replacements	451,000	925,614	0.01	917	1,882	AEROBIC	AEROBIC
TURKEYS							
Light	819,000	1,400,215	0.04	3,078	5,262	AEROBIC	AEROBIC
Heavy	1,131,000	1,933,630	0.09	12,968	22,171	AEROBIC	AEROBIC
HORSES	75,000	75,000	5.0	136,875	136,875	AEROBIC	AEROBIC
TOTAL FROM MANURE				1,068,931	1,397,135	58,315	72,657

ANNUAL METHANE PRODUCTION FROM WILDLIFE RUMINANTS

ANIMAL CLASS		1990 ANIMAL NUMBERS	2005 ANIMAL NUMBERS	ANNUAL METHANE PRODUCTION KG.	1990 METHANE PRODUCTION TONNES	2005 METHANE PRODUCTION TONNES
Moose		175,000	201,250	17.24	3,017	3,469
Elk		40,000	46,000	13.89	556	639
Carbou		14,000	16,100	9.39	131	151
SHEEP						
	Thinhorn	12,000	13,800	5.05	61	70
	Bighorn	7,700	8,855	7.09	55	63
Mountain Goat		56,000	64,400	6.10	342	393
DEER						
	Black-tailed	350,000	402,500	5.05	1,768	2,033
	White-tailed	48,000	55,200	5.05	242	279
TOTAL WILDLIFE RUMINANTS					6,170	7,096

WILDFIRES AVE. FUEL CONSUMPTION 67.00 tonnes/ha
AVERAGE EMISSION FACTOR 3.50 GRAMS/KILOGRAMS

Region	1990 HECTARES BURNT	2005 HECTARES BURNT Forecast	1990 METAHNE TONNES	2005.00 METAHNE TONNES
Vancouver	10713		2512	
P.Rupert	5444		1277	
P.George	55644		13049	
Kamloops	817		192	
Nelson	373		87	
Cariboo	2374		557	
Total Hectares	75365	108000		
TOTAL EMISSIONS FROM WILDFIRES			17673	25326

WETLANDS

PHYSIOGRAPHIC REGION	Beaver Ponds	Marshes	Fens & Swamps	Bogs	Total
					km2
Hecate Depression	2%	2%	10%	86%	1,395
Georgia Depression	2%	2%	40%	56%	267
Southern Plateau	4%	76%	20%	-	438
Chilcotin-Cariboo	4%	56%	40%	-	1,913
Central Plateau	4%	20%	66%	10%	2,356
Northwestern Plateau	4%	5%	56%	35%	576
Liard Plain	4%	2%	54%	40%	522
Fort Nelson Lowland	2%	2%	30%	64%	21,491
Peace River Lowland	2%	2%	34%	60%	4,666
Mountains	2%	10%	31%	55%	710
					34,334

	Beaver Ponds 15.00	Marshes 20.00	Fens & Swamps 5.00	Bogs 0.50	Total
	tonnes/year using above emission rates in g/m2.yr				
	419	558	698	600	2,274
	80	107	534	75	796
	263	6,658	438	0	7,358
	1,148	21,426	3,826	0	26,399
	1,414	9,424	7,775	118	18,730
	346	576	1,613	101	2,635
	313	209	1,409	104	2,036
	6,447	8,596	32,237	6,877	54,157
	1,400	1,866	7,932	1,400	12,598
	213	1,420	1,101	195	2,929
TOTALS WETLANDS	12,042	50,840	57,562	9,470	129,913

APPENDIX V

SIMPLIFIED DESCRIPTION OF THE CHEMISTRY OF METHANE IN THE ATMOSPHERE

In the oxidation of methane to carbon dioxide, which occurs over a number of reaction sequences or steps, the first produces formaldehyde (CH_2O). In this step, the first reaction removes methane by oxidation with OH:

$$CH_4 + OH \rightarrow CH_3 + H_2O$$

and after subsequent reactions in which OH is produced, the overall reaction is:

$$CH_4 + 2\,NO + 2\,O_2 \rightarrow CH_2O + 2\,NO_2 + H_2O$$

Overall, OH acts as a catalyst (it initiates the chain of reactions leading to the above overall equation, but is a product in a later reaction so no net change in OH levels is observed), peroxy radicals (HO_2 and $CH_3\,O_2$) act as chain carriers, and NO is oxidized to NO_2. In a subsequent step NO_2 may be involved in a photolysis reaction leading to the formation of ozone. The net equation accounting for this is then:

$$CH_4 + HO_2 \rightarrow CH_2O + 2\,O_3 + H_2O$$

The product formaldehyde (CH_2O) is either removed from the atmosphere by deposition (wet or dry) or it undergoes further reaction, either in another catalytic cycle with OH to produce CO, NO_2 and H_2O, or a photolysis reaction yielding CO, 2 NO_2 and 2 OH (N.B. additional radicals in the second case).

An air quality problem related to the atmospheric chemistry of CH_4 is the result of the chain termination reactions for the radicals, OH_2 and OH, formed in the production of formaldehyde. The OH_2 radical contributes to the formation of nitric acid (HNO_3), and OH is involved in the production of hydrogen peroxide (H_2O_2). Hydrogen peroxide is damaging to vegetation, and also contributes to the formation of sulphuric acid. Both nitric and sulphuric acid are important components of acid rain. Other routes exist for the chain termination of the peroxy radicals but the most dominant reaction in a given situation depends on NO_x levels. Methyl peroxy radicals (CH_3OO) may combine to form methoxy radicals (CH_3O) and O_2 and so avoid a chain terminating step.

In the oxidation of carbon monoxide both NO_2 and CO_2 are produced initially according to the reaction

$$CO + NO + O_2 \rightarrow CO_2 + NO_2,$$

in which again OH acts as a catalyst.

The NO_2 as noted previously undergoes a photolysis reaction, yielding ozone, so that the overall reaction for conversion of CO to CO_2 becomes:

$$CO + 2O_2 + h\nu \rightarrow CO_2 + O_3$$

APPENDIX VI

CALCULATION OF METHANE SINK
BY LU AND KHALIL

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JUL 2 4 1991

Removal of Methane by OH in British Columbia

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The current loss of atmospheric methane in British Columbia (366,255 mile^2) is **0.49 (0.39~0.61) Tg/year** (1 Tg = 10^{12} gram), by using following formula:

$$Q = \alpha \sum_i \sum_k \sum_j K_j \cdot [OH]_{ijk} \cdot [CH_4]_{ijk} \cdot \Delta Z_j \cdot \Delta S_k \qquad (1)$$

where $\alpha = M \cdot t/(N_0 \cdot \beta)$ is a unit conversion factor; M is the molecular weight of CH_4, 16 g/mole; $N_0 = 6.02297 \times 10^{23}$ mole^{-1} is Avogadro's number; $\beta = 10^{-12}$ g/Tg; $t = 365 \times 24 \times 3600/4$ second is the length of time of one season; subscript i, j, and k are the designators of season, altitude, and latitude, respectively (i=1, ..., 4; j=1, ..., 25; and k=1, 2, 3); K is the chemical reaction rate for the reaction between OH and CH_4 at the *j*th altitude (DeMore et al., 1985); $[OH]_{ijk}$ is the durnally averaged OH concentration in the *i*th season at the *j*th altitude and the *k*th latitude, which is derived from the results of our photochemical model (Lu, 1990; Lu and Khalil, 1991a,b) and Spivakovsky et al. (1990); $[CH_4]_{ijk}$ is the concentration of CH_4 derived from the CH_4 observation data in 1987 (Khalil and Rasmussen, 1987) and our understandings of current global atmospheric methane trend (Khalil and Rasmussen, 1990); ΔZ_j is the distance between two adjacent nodes at the *j*th altitudes; ΔS_k is the sub-area centered at the *k*th latitude. We also calculated the amount of methane removed by OH in each season (Table 1).

We estimate the soil sink to be between 0.1 ~ 0.4 Tg/year based on annual global of 20 ~ 50 Tg/year. The loss of methane in the stratosphere is very small compared to that in the troposphere.

Table 1. The loss of atmospheric methane due to reaction with OH in the four seasons and the annual loss in 1987, and the current loss in British Columbia.

	Loss of Methane (Tg)				
	Winter	Spring	Summer	Fall	Annual
1987	5.55×10^{-3}	0.101	0.295	0.0744	0.476
Now	5.72×10^{-3}	0.104	0.304	0.0767	0.491

Appendix

1. The rate of the reaction between OH and CH_4 is taken from *NASA* (1985):

$$K(Z) = 2.4\times10^{-12}\exp(-1710/T) \qquad (A1)$$

where T is atmospheric temperature at height Z, and the model atmosphere adopted is U. S. Standard Atmosphere (U. S. Standard Atmosphere, 1976); i.e.,

$$T = 288.15 - 0.0065Z \qquad (A2)$$

2. The methane level is based on the measurements at Barrow, Alaska (72 ° N) and Cape Meares, Oregon (45 ° N) in 1987 (Khalil and Rasmussen, 1987). A 3% increase is assumed for the current level of CH_4. the concentrations of CH_4 are shown in the table A1.

Table A1. The concentrations of CH_4 in the four seasons at two latitudes.

	Methane (ppbv)							
	Cape Meares (45 °N)				Barrow (72 °N)			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
1987	1739	1734	1719	1756	1773	1767	1743	1773
Now	1791	1786	1770	1808	1827	1820	1795	1826

The vertical profiles of CH_4 (in unit of molecules/cm^3) were calculated by using the idea gas law:

$$[CH_4] = 10^{-6}\frac{N_0 \cdot P}{R \cdot T} \qquad (A3)$$

where $R=8.314\ J\cdot mole^{-1}\cdot {}^\circ K^{-1}$ is the universal gas constant; $N_0=6.023\times10^{23}$ molecules/mole is the Avogadro's number; T is the temperature (° K), expressed as eq. (2A); P (N/m^2) is the pressure, expressed as following equation:

$$P = 101325(288.15/T)^{-5.255877} \qquad (A4)$$

Using linear interpolation formula, we calculated the vertical profiles of methane at any latitude between 48 ° N and 60 ° N.

3. The vertical profiles of OH in this study were obtained by using the vertical profiles of the diurnally averaged OH concentrations at 45 ° N, taken from table A.3.1. from Lu and Khalil (1991), and using latitudinal distribution of OH (Spivakovsky et al, 1990), as shown in the following table:

Table A2. Vertically and Diurnally Averaged OH Concentrations (in 10^5 molecules/cm^3), derived from Spivakovsky et al (1990):

Season	Winter			Spring			Summer			Fall		
Lati. (° N)	60	52	44	60	52	44	60	52	44	60	52	44
[OH]	0.0527	0.301	0.843	3.25	3.91	5.48	9.14	10.6	12.9	0.677	1.61	3.22

Using linear interpolation formula, the vertically and diurnally averaged OH concentration respectively at 45 ° N, 48 ° N, and any latitudes between 48 ° and 60 ° N were calculated. Thus the diurnally averaged OH concentration in the *i*th season at the *k*th latitude and at the *j*th altitude, $[OH]_{kji}$, can be obtained by the following formula:

$$[OH]_{kji} = \frac{\overline{[OH]}^{S}_{ki}}{\overline{[OH]}^{S}_{1i}} \cdot [OH]^{L}_{ji} \qquad (A4)$$

$\overline{[OH]}^{S}_{ki}$ and $\overline{[OH]}^{S}_{1i}$ are the vertically and diurnally averaged OH concentrations in the *i*th season, respectively at the *k*th latitude and at 45 ° N, derived from table A2; $[OH]^{L}_{ji}$ is the diurnally averaged OH concentration at the *j*th altitude in the *i*th season, taken from table A.3.1.

4. Summary & discussions:

a. If we choose the vertical profiles of OH and CH_4 at 54 ° N (the center of B.C.) as the representative values for the whole B.C. (single-area method), the loss of CH_4 due to OH in B.C. is shown in table A3. The range of the total loss of CH_4 due to OH in B.C. (0.39~0.61) was obtained by respectively taking the vertical profiles of OH and CH_4 at the highest and the lowest latitudes of B.C. (60 ° N and 48 ° N) as representative values for the whole B.C.

Table A3. The loss of atmospheric methane due to reaction with OH in the four seasons and the annual loss in 1987, and the current loss in British Columbia.

	Loss of Methane (Tg)				
	Winter	Spring	Summer	Fall	Annual
1987	4.82×10^{-3}	0.0980	0.292	0.0702	0.465
Now	4.96×10^{-3}	0.101	0.301	0.0723	0.479

b. Latitudinally dividing the whole B.C. into 2 equal size sub-areas, we obtained the loss of CH_4 in B.C. in table 1 using the vertical profiles of OH & CH_4 at 48 ° N, 54 ° N, and 60 ° N.

c. Latitudinally dividing the whole B.C. into 6 equal size sub-areas, we obtained the loss of CH_4 in B.C. in table A4 using the vertical profiles of OH & CH_4 at 48 ° N, 50 ° N, ..., and 60 ° N.

Table A4. The loss of atmospheric methane due to reaction with OH in the four seasons and the annual loss in 1987, and the current loss in British Columbia.

	Loss of Methane (Tg)				
	Winter	Spring	Summer	Fall	Annual
1987	5.31×10^{-3}	0.100	0.294	0.0730	0.473
Now	5.47×10^{-3}	0.103	0.303	0.0752	0.487

d. There are only slight differences of estimates of the loss of CH_4 in B.C. among the single-area method, the two-sub-area method, and the 6-sub-area method.

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Appendix 3 The Diurnally Averaged OH Concentrations

Table A.3.1. The diurnally averaged OH concentrations (10^{5} molecules/cm^{3}) at 45°N and 45°S.

Height	Dec.-Jan.		Mar.-Apr.		Jun.-Jul.		Sec.-Oct.		Annual	
(km)	45°N	45°S	45°N	45°S	45°N	45°S	45°N	45°S	45°N	45°S
0.0	0.88	18	6.6	8.3	18	0.95	7.0	7.3	8.1	8.8
0.5	0.91	18	7.2	7.9	20	1.1	8.1	7.0	8.9	8.4
1.0	0.92	16	7.6	7.3	21	1.1	8.9	6.5	9.7	7.8
1.5	0.94	15	7.7	6.9	22	1.0	8.8	5.9	9.8	7.2
2.0	0.95	14	7.7	6.3	21	0.90	8.7	5.3	9.7	6.6
2.5	0.92	14	7.4	6.1	20	0.87	8.3	5.3	9.3	6.5
3.0	0.87	13	7.1	5.7	19	0.84	7.9	5.1	8.8	6.2
3.5	0.79	13	6.8	5.3	18	0.78	7.4	4.9	8.3	5.9
4.0	0.68	11	6.5	4.9	16	0.72	6.8	4.6	7.6	5.4
4.5	0.62	11	6.3	4.7	15	0.70	6.5	4.6	7.2	5.3
5.0	0.55	11	6.1	4.6	14	0.68	6.2	4.5	6.7	5.2
5.5	0.48	11	5.7	4.4	13	0.65	5.7	4.3	6.1	5.1
6.0	0.40	10	5.2	4.2	11	0.61	5.2	4.1	5.4	4.8
6.5	0.36	10	5.1	4.2	10	0.59	5.2	4.2	5.2	4.8
7.0	0.32	10	4.9	4.2	10	0.57	5.1	4.2	5.1	4.8
7.5	0.28	9.9	4.6	4.2	9.4	0.53	5.0	4.1	4.8	4.7
8.0	0.24	9.6	4.3	4.2	8.6	0.50	4.8	4.0	4.5	4.6
8.5	0.21	9.9	4.0	4.2	8.6	0.47	4.6	4.0	4.4	4.6
9.0	0.18	10	3.8	4.2	8.5	0.44	4.3	4.0	4.2	4.7
9.5	0.15	10	3.4	4.1	8.4	0.41	4.0	3.8	4.0	4.6
10.0	0.12	10	3.0	4.0	8.2	0.38	3.6	3.6	3.7	4.5
10.5	0.11	10	2.7	3.9	8.2	0.35	3.3	3.5	3.6	4.5
11.0	0.095	10	2.4	3.8	7.9	0.32	3.0	3.3	3.3	4.5
11.5	0.080	9.9	2.0	3.6	7.0	0.29	2.5	3.0	2.9	4.2
12.0	0.051	8.6	1.3	3.1	4.6	0.22	1.7	2.5	1.9	3.6

APPENDIX VII

MASTER LIST OF CONTROL MEASURES

Master List of Methane Emission Mitigation Measures - Technical Options

Sector	1990 CH4 Emissions (kt)	Potential Control Measure	Technical Emission Reduction Potential (Low/ Moderate/ High)	Cost (Low/ Moderate/ High)	Ease of Implementation (Low/ Moderate/ High)	Status (Proven/ Emerging/ Unknown)	Timeframe (Short: < 3 Yrs; Med: 4-10 Yrs; Long: > 10 Yrs)
ANTHROPOGENIC SOURCES							
INDUSTRIAL COMBUSTION							
Utility Power	0.00	Boiler Tuning	L	L	H	P	S
		Load Reduction/Demand Management	M	L	M	P	S-M
		Cogeneration (electricity, and process & bldg heat)	M	M	L	E-P	M-L
Industrial Power	0.04	Boiler Tuning	L	L	H	P	S
		Load Reduction/Demand Management	M	L	M	P	S-M
		Switching to NGAS	M	M-H	L	P	L
		Combined Cycle elec. Generation - Turbine exhaust used as preheated comb. air for boilers					
		Cogeneration (electricity, and process & bldg heat)	M	M-H	L	E-P	M-L
Residential	0.19	High Efficiency Furnace & appliances	M	M	M	P	M-L
		Retrofit existing furnace to NGAS	M	H	M	E-P	S-M
		Insulate- new homes (Yr 2000)/Bldg. Design Standards	M	L	H	P	S
		Insulation upgrade - existing residences	M	H	L	P	S
		Energy Conservation - Public Education	L-M	L	M	P	S
Commercial	0.11	Insulate- new Bldgs. (Yr 2000)/Bldg Design Standards	M	L	H	P	S
		Insulation upgrade - existing buildings	M	H	L	P	S
		Switching to NGAS	M	M-H	L-M	P	L
		Heat pumps	L	H	L-M	E-P	S
Pulp & Paper	0.25	Boiler Tuning	L-M	L	H	P	S
		Improved Energy Efficiency	M	M	M	P	S-M
		Switching to Natural Gas	M	M-H	L	P	L
		Bldg Design Standards (New Facilities)	L	L	H	P	S
		Cogeneration (electricity, and process & bldg heat)	M	M-H	L	E-P	M-L
Wood Products	0.14	Cogeneration (electricity, and process & bldg heat)	M	M-H	L	E-P	M-L
		Bldg Design Standards (New Bldgs)	L	L	H	P	S
		Switching to Natural Gas	M	M-H	M	P	S-M
Primary Metals	0.00	Improved Equipment for Heat Treating and non-ferrous furnaces, and advanced and regenerative burners	M	M-H	L-M	E-P	M-L
		Cogeneration (electricity, and process & bldg heat) for:	M	M-H	L-M	E-P	M-L
		Bldg Design Standards (New)	L	L	H	P	S
		Improved Energy Efficiency	M	M	M	P	S-M
Chemical Industries	0.01	Improve fugitive emissions technology, eg. for valve packing, mechanical seals, valve back seating, and operational practices	M	M	M	P	S-M
		Cogeneration (electricity, and process & bldg heat)	M	M	L	E-P	M-L
		Bldg Design Standards (New)	L	L	H	P	S
		Improved Energy Efficiency	M	M	M	P	S-M
Non-Metallic Industries	0.01	Bldg Design Standards (New)	L	L	H	P	S
		Improved Energy Efficiency	M	M	M	P	S-M

Master List of Methane Emission Mitigation Measures - Technical Options

Sector	1990 CH4 Emissions (kt)	Potential Control Measure	Technical Emission Reduction Potential (Low/ Moderate/ High)	Cost (Low/ Moderate/ High)	Ease of Implementation (Low/ Moderate/ High)	Status (Proven/ Emerging/ Unknown)	Timeframe (Short: < 3 Yrs; Med: 4-10 Yrs; Long: > 10 Yrs)
Petroleum Refining	0.04	Improve fugitive emissions technology (LDAR)	M	M	M	P	S-M
		eg. for valve packing, mechanical seals, valve					
		back seating, and operational practices					
		Cogeneration (electricity, and process & bldg heat)	M	M	L	E-P	M-L
		Improved Energy Efficiency	M	M	M	P	S-M
Mining	0.10	Improved Energy Efficiency	M	M	M	P	S-M
		Bldg Design Standards (New)	L	L	H	P	S
		Cogeneration (electricity, and process & bldg heat)	M	M	L	E-P	M-L
Other Manufacturing	0.03	Improved Energy Efficiency	M	M	M	P	S-M
		Bldg Design Standards (New)	L	L	H	P	S
		Cogeneration (electricity, and process & bldg heat)	M	M	L	E-P	M-L
Other Industries	0.16	Improved Energy Efficiency	M	M	M	P	S-M
		Bldg Design Standards (New)	L	L	H	P	S
		Cogeneration (electricity, and process & bldg heat)	M	M	L	E-P	M-L
SUB TOTAL INDUSTRIAL COMBUSTION	1.07						
MOBILE SOURCES		Fuel Switching - New Cars (eg Electric Cars)	L-M	M-H	L-M	E	M-L
Road Gasoline Vehicles	6.64	Retrofit vehicles for alternate fuels (with rebates from	L-M	M-H	L-M	E-P	S-M
Road Diesel Vehicles	0.29	carbon or fossil fuel tax)					
		Transportation Control Measures (Policy)	L-M	L-M	L-M	P	S-M
		Insurance for car pools, Stickers to drive downtown,					
		Emissions I/M, Traffic Planning- Synchronised lights,					
		Limit truck traffic downtown and at rush hour (Less congestion)					
		Open a side-street route for bikes only at rush hour for D/T commute					
		Mass Transit Incentives- Park'n'ride, Employers supply tickets &					
		not parking, Better service (Convenience & Safety)					
		Beater buy back programs (eg. funded by carbon tax)					
		Land Use Planning - Short Commutes (Policy)	L-M	M	M-H	P	M-L
		High Mileage (& Safety) Standards	L-M	M	M	E	M-L
Aircraft	0.40	Upgrade fuel-efficiency	L	H	L	P	L
		Reduce airport congestion					
Marine	1.30	Upgrade fuel-efficiency	M	M-H	L-M	P	M-L
		Fuel Switching	M	M-H	L	E-P	M-L
Railroad	0.10	Upgrade fuel-efficiency	M	H	L	P	L
Off-Road Vehicles	0.26	Upgrade fuel-efficiency	M	M	L	E-P	M-L
		Fuel Switching	M	M-H	L-M	E-P	M-L
SUB TOTAL MOBILE SOURCES	8.99						

Master List of Methane Emission Mitigation Measures - Technical Options

Sector	1990 CH4 Emissions (kt)	Potential Control Measure	Technical Emission Reduction Potential (Low/ Moderate/ High)	Cost (Low/ Moderate/ High)	Ease of Implementation (Low/ Moderate/ High)	Status (Proven/ Emerging/ Unknown)	Timeframe (Short: < 3 Yrs; Med: 4-10 Yrs; Long: > 10 Yrs)
INCINERATION							
Woodwaste	6.70	Energy Generation Systems	H	M-H	M-H	P	M-L
		Improved Incinerators	M	L	M	P	M
		Production of Wood products	H	H	L	P	M-L
Fraser River Debris	0.04	Energy Generation	H	H	L	P	M
MSW	0.05	Incinerator Tune-Up	L-M	L	H	P	S
		Cogeneration - Displace other fuel use	L	M-H	L-M	P	M-L
SUB TOTAL INCINERATION	6.80						
NATURAL GAS		Replace continuous bleed controllers with air, electronic or intermittent bleeds	L-M	M	L-M	P	S-M
		Improve fugitive emissions technology, eg. for valve packing, mechanical seals, valve back seating, and operational practices	L-M	M-H	L-M	E-P	S-M
		Leak Detection and Repair Programs	L-M	L-M-H	L-M	E-P	S-M
		Improved Energy Efficiency	L-M	M	L-M	P	M-L
		Emissions trading (Policy)					
		Emission fees (Policy)					
		Provide a 24-hr phone # for questions on digging -> avoid accidents (Policy)					
		Ban venting of nat'l gas; collect and recover energy or flare(Policy)					
		Portable Gas Compressor to reduce losses from gas line maintenance	M	M	M	P	S
Production	31.24	As above					
Processing	8.81	As above					
Transmission	2.15	As above					
Distribution	1.35	As above					
		Replace cast iron pipe, & employ leak detection system on new lines eg. cathodic leak detection	M	M	L	P	M
		Increase Odourant Levels	L	M	M	P	S
		Smart Meters for residential & commercial users	L	L-M	M	E-P	S-M
		Demand-Side Management	M	L-M	M	P	S
SUB_TOTAL NATURAL GAS	43.56						
OIL							
Production	17.03	Vapour Recovery Systems Upgrade	L	M-H	L-M	P	M-L
		Replace continuous bleed controllers	M-H	M	M	P	S-M
		Improve fugitive emissions technology, eg. for valve packing, mechanical seals, valve back seating, and operational practices	L-M	M	L-M	E-P	S-M
		Leak Detection and Repair Programs	L-M	L	M	P	S
		Improved Energy Efficiency	L-M	M-H	L-M	E-P	M-L

Master List of Methane Emission Mitigation Measures - Technical Options

Sector	1990 CH4 Emissions (kt)	Potential Control Measure	Technical Emission Reduction Potential (Low/ Moderate/ High)	Cost (Low/ Moderate/ High)	Ease of Implementation (Low/ Moderate/ High)	Status (Proven/ Emerging/ Unknown)	Timeframe (Short: < 3 Yrs; Med: 4-10 Yrs; Long: > 10 Yrs)
		Emissions trading (Policy)					
		Permit Emission fees (Policy)					
Transportation	0.25	Vapour Recovery Systems Upgrade	L	H	L-M	P	S-M
		Leak Detection and Repair Programs	L	L	M	P	S
		Improve fugitive emissions technology, eg. for valve packing, mechanical seals, valve back seating, and operational practices	L	M	M	E-P	S-M
SUB-TOTAL OIL	17.29						
LANDFILLS							
MSW	228.63	Gas Recovery for Energy Use (Rule of Thumb is 1 million tonnes in place and 15 metres deep)	H	M-H	M	P	S-M
		Gas Recovery for Incineration	L-M	M	M	P	S-M
		Reduce MSW by recycling, source reduction, composting, waste to energy (WTE), or incineration.	M	M	M	P	L
Woodwaste	49.32	Alternative Use of Wastes (eg. energy, wood products)	H	M	L-M	P	M-L
		Reduced Waste Generation at Mill	M	M-H	L	P	M-L
Pulpwaste	12.46	Use as Fuel	H	L-M	M-H	P	S-M
		Land Application	H	M	L-M	P	M
		Reduced Waste Generation at Mill	M	H	L	P	M-L
SUB-TOTAL LANDFILLS	290.41						
COAL MINES	51.60	Degasification (Prior to and during mining operations)	L-M-H	M-H	L-M	E-P	M-L
		Horizontal and Cross Measure Boreholes (Underground Mines)	L	M-H	L-M	E-P	M-L
		Vertical Wells from surface	H	H	L	E-P	M-L
PRESCRIBED FIRES	17.74	Increased recovery for use as fuel	M	H	M	P	M-L
		Increased Fiber recovery	L	H	M	P	M-L
DOMESTIC ANIMALS							
Beef Cattle	24.60	Hormone Implants	L	H	H	P	S
		Ionophores (More efficient food use)	L	H	M	P	S
		Bovine SomatoTrophins (BST)	L	H	L	P	M
		Feed Management	L-M	H	H	P	S
		Protein Supplement	M	M-H	M	P	S
Dairy Cattle	10.88	Bovine SomatoTrophins (BST)	L	H	H	P	M
		Feed Management	L	M	H	P	S
		Aerobic Digestion	M	M-H	L-M	P	S-M
Horses	1.24						

Master List of Methane Emission Mitigation Measures - Technical Options

Sector	1990 CH4 Emissions (kt)	Potential Control Measure	Technical Emission Reduction Potential (Low/ Moderate/ High)	Cost (Low/ Moderate/ High)	Ease of Implementation (Low/ Moderate/ High)	Status (Proven/ Emerging/ Unknown)	Timeframe (Short: < 3 Yrs; Med: 4-10 Yrs; Long: > 10 Yrs)
Other	0.90						
SUB_TOTAL DOMESTIC ANIMALS	37.62						
MANURE							
Beef Cattle	2.15	Composting	H	L	L	P	S
		Dry & Sell - Soil conditioner	M	L	M	P	S
Dairy Cattle	44.33	Composting	H	L	L	P	S
		Dry & Sell - Soil conditioner	M	L	M	P	S
		Fuel - Methane digester	H	L-M	L	P	S
		Aerobic on-farm use	H	M	M	P	S
Other	11.84						
SUB_TOTAL MANURE	58.32						
TOTAL ANTHROPOGENIC	533.38						
NATURAL SOURCES							
WILDLIFE	6.15						
WILDFIRES	17.67						
WETLANDS	129.91						
LAKES AND RIVERS	0.02						
TOTAL NATURAL SOURCES	153.75						
TOTAL ALL SOURCES	687.13						

N.B.: Alternative Fuels: Wind, Hydro/Tidal, Geothermal, Solar, Nuclear

Master List of Methane Emission Mitigation Measures - Economic Measures and Other Incentives

Sector	Potential Control Measure	Emission Reduction Potential (Low/ Moderate/ High)	Cost (Low/ Moderate/ High)	Ease of Implementation (Low/ Moderate/ High)	Status (Proven/ Emerging/ Unknown)	Timeframe (Short: < 3 Yrs; Med: 4-10 Yrs; Long: > 10 Yrs)
All	Taxes & Rebates (Revenue-Neutral Program) or Carbon tax used to finance retrofitting vehicles for alternative fuels; improve transit service; fund rebates on high efficiency appliances; and/or in beater buy-back programs (where any high emitting vehicle -typically 10 yrs old or more- is referred to as a beater). Alternatives are carbon, fossil fuel or greenhouse gas tax. Other monetary incentives such as subsidies for env. friendly products.	M	L	M	E	M-L
All	Emissions Fees	L-M	L	M	E	M-L
All	Emissions Trading	M	M	L-M	E	M-L
All	Energy Conservation	M	M	M	E-P	M-L
All	Government Procurement Policies	L	L-M	M	E-P	M-L
Overlaps mobile sources, residential, commercial etc.	Land Use Planning, to reduce emissions through: i) Shorter Commuting Distances ii) Building Design Standards	L-M	L-M	M	E-P	M-L

APPENDIX VIII

LIST OF ACRONYMS

LIST OF ACRONYMS

CARB	California Air Resources Board
CBM	Coal Bed Methane
CGA	Canadian Gas Association
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COFI	Council of Forest Industries
CPA	Canadian Petroleum Association
CPPA	Canadian Pulp & Paper Association
DE	Digestible Energy
EMPR	Energy Mines and Petroleum Resources
ERCB	Energy Resources Conservation Board
GVRD	Greater Vancouver Regional District
H_2O	Water
HDDV	Heavy Duty Diesel Vehicles
HDGV	Heavy Duty Gasoline Vehicles
HVP	High Vapour Pressure
ICBC	Insurance Corporation of B.C.
IERD	Industry Energy Research and Development
LDAR	Leak Detection and Repair
LDDT	Light Duty Diesel Trucks
LDDV	Light Duty Diesel Vehicles
LDGT1	Light Duty Gasoline Trucks 1
LDGT2	Light Duty Gasoline Trucks 2
LDGV	Light Duty Gasoline Vehicles
LPG	Liquified Petroleum Gas
LVP	Low Vapour Pressure
MC	Motorcycles
ME	Metabolizable Energy
MSW	Municipal Solid Waste
NMHC	Non-Methane Hydrocarbons
NMOC	Non-Methane Organic Compounds

LIST OF ACRONYMS

NO_x	Nitrogen Oxide
O_3	Ozone
OH	Hydroxyl
ONGA	Ontario Natural Gas Association
RDF	Refuse-Derived Fuel
TCM	Transportation Control Measures
THC	Total Hydrocarbon
VKmT	Vehicle Kilometre Travelled
VOC	Volatile Organic Compounds

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